THESIS ON CIVIL ENGINEERING F63

Stormwater Quantity and Quality of Large Urban Catchment in Tallinn

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I hereby declare that this doctoral thesis, my original investigation and achievement, submitted for doctoral degree at Tallinn University of Technology has not been submitted for any academic degree.

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CONTENTS

LIST OF PUBLICATIONS CONSTITUTING THE THESIS

The thesis is based on four publications in international peer-reviewed journals. The publications are referred to in the text as Paper I, Paper II, Paper III and Paper IV.

Paper I: Maharjan, B.; Pachel, K.; Loigu, E.; 2013. *Urban stormwater quality and quantity in the city of Tallinn.* European Scientific Journal, 3, 365-375.

Paper II : Maharjan, B.; Pachel, K.; Loigu, E. (2016). *Trends in urban stormwater quality in Tallinn and influences from stormflow and baseflow.* Journal of Water Security, 2 (1), 1−11, 10.15544/jws.2016.001.

Paper III: Maharjan, B.; Pachel, K.; Loigu, E. (2016). *Towards effective monitoring of urban stormwater for better design and management.* Estonina Journal of Earth Sciences, 65(3), 176-199, 10.3176/earth.2016.12.

Paper IV: Maharjan, B.; Pachel, K.; Loigu, E. (2016). *Modeling of stormwater runoff and quality loadings and the impact of directly connected impervious area in the large urban catchment.* (Accepted in Proceedings of the Estonian Academy of Sciences, in print).

AUTHOR´S CONTRIBUTION TO THE PUBLICATIONS

Paper	Original idea	Study design and methods	Data collection and handling	Contribution to result interpretation and manuscript preparation	Responsible for result interpretation and manuscript preparation
I	BM	BM	TUT DEE, BM	BM, EL, KP	BM
II	BM	BM	TUT DEE, BM	BM, EL, KP	BM
III	BM	BM	TUT DEE, BM	BM, EL, KP	BM
IV	BM	BM	TUT DEE, BM	BM, EL, KP	BM

BM- Bharat Maharjan
EL - Enn Loigu
KP - Karin Pachel
TUT DEE – Tallinn University of Technology, Department of Environmental Engineering

ABBREVIATIONS AND TERMS

ADD - antecedent dry days

BMP - best management practices

BOD- biochemical oxygen demand

CC - correlation coefficient

COD - chemical oxygen demand

CV - coefficient of variance

DCIA - directly connected impervious area

DEM - digital elevation model

DNCIA - directly not connected impervious area

DOC - dissolved organic carbon

E. coli - Escherichia Coli

EC - electric conductivity

EIA - effective impervious area

EMC - event mean concentration

EPA - Environmental Protection Agency

EU - European Union

EU WFD - European Water Framework Directive

GIS - geographical information system

Gov. Reg. No. 99 - Governmental Regulation no. 99, 29 November 2012, entry into force since 01.01.2013 “The requirements of wastewater treatment and discharging waste- and stormwater to the recipient, the limit values for waste and stormwater pollution indicators and the control measures of the compliance check”

HC - hydrocarbons

HELCOM - The Baltic Marine Environment Protection Commission (Helsinki Commission)

ISO - International Organization for Standardization

MK - Mann Kendall

NOF - normalised objective function

NSF - Nash-sutcliffe coefficient

PAH - polyaromatic hydrocarbon

PCB - polychlorinated biphenyl

PE - population equivalent: a measure of pollution representing the average organic biodegradable load per person per day. It is defined in Directive 91/271/EEC as the organic biodegradable load having a five-day biochemical oxygen demand of 60 g of oxygen per day.

RE - relative error

RSE - relative standard error

SMC - site mean concentration

SMK - Seasonal Mann Kendall

SS - suspended solids

SWMM - stormwater management model

TDS - total dissolved solids

TIA - total impervious area

TN - total nitrogen

TOC - total organic carbon

TP - total phosphorus

TSS - total suspended solids

TUT - Tallinn University of Technology

WWTP - wastewater treatment plant

1. INTRODUCTION

Stormwater in the world is garnering greater attention as extreme events become more frequent, increasing the cases of flooding and pollution load to receiving waterbodies, and in particular increasing mass load and eutrophication in coastal areas. Water protection and ecological restoration have been goals for many countries for some time and they have enforced acts and regulation individually and in a combined way towards this end. In that regard, the current status and change over the years in stormwater pollutant concentrations provide information about the effectiveness of the initiatives. It is essential in stormwater management to obtain information regarding the level and source of pollution, compliance evaluation of the pollution reduction activities and feedback for further improvements. For these, the monitoring programmes should acquire the representative data of all storm events because the uncertainties in the prediction of runoff and pollution load can be misleading in many regards e.g. misconception on the stormwater quality and quantity, inappropriate and ineffective control designs and location as well as weak stormwater management strategies. In addition, a resource constraint always interfers performing comprehensive monitoring programme in many countries. In this study, the measures to approach the actual runoff and pollution load are investigated in cases where limited resources are available. To ensure effective management strategies, it requires the introduction at an early stage of a suitable monitoring programme, effective control measures and predictive instruments that balance the available resources.

1.1. Regulation in Stormwater management

Water is a precious natural commodity that needs to be protected and preserved. In the US, the national pollution discharge elimination system permit programme has regulated the control of point source pollution from urban stormwater, industrial discharges and construction activities. In Australia and New Zealand, the national stormwater guidelines-2000 have been the regulatory documents in striving to achieve sustainable use of the nation's water resources by protecting and enhancing their quality while maintaining economic and social development. In Europe, the EU member states have created a common ground with the EU water framework directive in protecting water resources. The main environmental objectives are to achieve and maintain a good status for all surface waters, including coastal waters and groundwaters. The target date was 2015, but this has been derogated out to 2027, with three cycles: 2015, 2015-21 and 2021-27. By 2015, much progress had been made in water protection in Europe, in individual Member States, and in tackling significant problems at European level. But water protection is still a great challenge and requires increased efforts with the involvement of citizens to get Europe's waters clean or keep them clean.

In regard to stormwater specifically, among the EU directives, the Urban Wastewater Directive (91/271/EEC) states that national authorities should ensure to take measures to limit the pollution of receiving waters from stormwater overflows via collecting systems under unusual situations, such as heavy rain. The more strignent regulation is from the HELCOM commission. As Estonia is a country in the Baltic Sea region, it is a requirement to undertake the recommendations of the Helsinki Commission (HELCOM) in addition to EU directives. Valid HELCOM recommendation 23/5 on the reduction of discharges from urban areas through the proper management of stormwater systems focuses on the runoff volume and first flush in a separate system and most polluted overflows in the combined system (HELCOM, 2002). Measures are recommended at the source to minimise the volume and prevent the deterioration of stormwater quality in separate and combined sewer systems. Similar to WFD, the aim of the HELCOM Baltic Sea Action Plan (BSAP) is to restore the good ecological status of the Baltic marine environment by 2021(HELCOM, 2007).

One of the main problems in the Baltic Sea region is eutrophication, in which Estonia also contributes substantially (Iital et al, 2010). Urban runoff also plays a substantial part in the degradation of coastal waters, including a rise in the nutrient level (King et al, 2007; Erm et al, 2014; TCG, 2015). Apart from eutrophication, the goal of BSAP is also that the Baltic Sea environment will not to be hampered by hazardous substances. Estonia enforces the requirements of EU directives and HELCOM recommendations through national acts and regulations. The Estonian Water Act (RTI, 2015b) regulates the activity of protecting all waters against pollution to achieve the good status and promoting sustainable water and wastewater. The Public Water Supply and Sewerage Act (RTI, 2016) regulates the collection and treatment of wastewater and stormwater, according to which the local government develops plans and activities for stormwater management. Outside the buildings, stormwater and sewerage system are constructed, rehabilited, maintained and operated according to the Estonian standard EVS 848:2013. The principle is based on returning stormwater to nature either by possible infiltration and delay at sources or by reuse. Based on the Water Act, Government Regulation no. 99 (Gov. Reg. No. 99), 29 November 2012 (RTI, 2013a) "The requirements of wastewater treatment and discharging waste and stormwater to the recipient, the limit values for waste and stormwater pollution indicators and the control measures of the compliance check" was adopted by the Government of Estonia. It provides threshold values for wastewater effluents, waste and stormwater dicharges as well as complaince verfication measures. According to the requirements of national and international regulations, it is essential to assess the status of stormwater for the compliance verification, such that the compreshensive interpretation of the monitoring data can be possible to form the basis for the planning and implementation of protection measures.

1.2. Stormwater dynamics in Tallinn

In the context of regional level, Tallinn has issues regarding the drainage system, as it encounters frequent flooding during heavy rainfalls and snowmelts (RTI, 2013b). Moreover, the pollution loads from stormwater outlets have a substantial part to play in coastal water degradation, especially in Tallinn Bay (Erm et al, 2014) and Kopli Bay (TCG, 2015). It is argued that they are one potential source for the impact on water transparency and depletion of the oxygen level; however, they found the long term negative dynamics in the Paljassaare and Miiduranna sea areas. Therefore, the trends of stormwater pollutants are essential for understanding the temporal changed share of pollutant discharges in the ecological status of coastal water. Some of the initiatives introduced in the 2000s by the City of Tallinn have begun to reduce runoff and pollution load. Many action plans and activities are formulated in the Tallinn Development Plan 2014–2020 (RTI, 2013b), Tallinn Stormwater Strategy to 2030 (RTI, 2012) and Tallinn Water Supply and Sewerage Development Plan 2010–2021, such as reducing the pollution load by street cleaning, minimising hydrocarbon through the installation of oil filters, reducing nutrients building treatment plants, the construction of separate system and the reconstruction of the combined sewer system, etc. The compliance of these initiatives with the reduction of pollutants needs to be ensured in the long-term and short-term in order to make decisions on further planning.

1.3. Approach to actual pollution load

In Estonia, the Environmental Monitoring Act (RTI, 2015a) directs environmental monitoring at three different levels. They are: national monitoring for a long-term programme undertaken under sectors including the Estonian Environmental Agency, Estonian Environmental Board and national institutions; local government monitoring by local authorities; and the monitoring by an undertaking body for the area affected by its activities or by discharged pollutants. The regional department of the Environmental Board under the Ministry of Environment issues special water permits to water users. According to the special water permit, water users or the owner of this permit should ensure the monitoring of wastewater and stormwater volumes as well as pollutant concentrations based on the locations and frequency specified by the permit. The permit issued by regional Environmental Boards establishes the rights and obligations for water users, including security measures and monitoring responsibilities related to water use. The Environmental Board is responsible for the organisation and verification of the compliance of monitoring activities. The local government provides a procedure for implementing the environmental monitoring programme and for processing and storing environmental monitoring data. Several studies investigate stormwater quantity and quality randomly, but they have only given a general picture of stormwater because all investigations are occasional not continuously functioning and characterising situation. The revised Environmental Charges Act (RTI, 2005) did not elicit the expected reduction in pollutant discharge into waterbodies because the stormwater pollution load is not easily measurable. A mean concentration to measure that backlogs assessing actual load and stormwater impacts to the receipients is yet unclear (Lääne & Reisner, 2011). The development of a stormwater monitoring programme in the Tallinn Development Plan 2014–2020 (Tallinn City Council Regulation no. 29, 13/06/2013) (RTI, 2013b) and the Tallinn Stormwater Strategy until 2030 (Tallinn City Council Regulation no. 18, 19/06/2012) (RTI, 2012) have been emphasised as important activities. Therefore, an effective and affordable monitoring programme is the first essential step towards stormwater management in Estonia.

In addition, the development of a model based on basin principle and providing stormwater drainage solutions are primary tasks for the Tallinn Development Plan. Indeed, they are the feasible solution for understanding stormwater dynamics within and beyond the period of study when only limited data resources are available. It is an alternative to extensive monitoring campaigns, which are largely constrained by technical problems (e.g. collection of representative samples) and resource availability (e.g. analytical equipment and budgets necessary for measurement) (Vezzaro & Mikkelsen, 2012).

The study proceeds with the investigation of the stormwater position in terms of quality and quanity in Tallinn where the data from different sources will be analysed. Further, the temporal change in stormwater concentrations and their possible causes will be analysed. Data representativeness and certainty of results are evaluated. Two ways of achieving good data will be investigated. First, the monitorting programmes in research literature will be sought out to provide a suitable sampling programme and to recommend an optimal and effective sampling programme that is suitable for Tallinn catchment area. The second is the development of modelling based on the pilot basin using limited data resources for estimating and predicting runoff and pollution load.

1.4. Objectives

The main objective of this thesis was to study the status of stormwater quantity and quality in Tallinn city as to provide possible solutions for its management in controlling runoff and pollution load. It was focused on four specific objectives, which were

1. to assess the stormwater quantity and quality status in the urban area of Tallinn city (Paper I).

2. to investigate the trends of stormwater quality over the years and the influence of dry and wet weather flow (Paper II).
3. to provide effective monitoring solutions for more effective stormwater management through reviews of numerous previous studies and ultimately to propose a general sampling programme for Tallinn (Paper III).
4. And, to develop a model application at limited resources to provide possible solutions for reducing stormwater runoff and pollution loads after analysing the pilot basin (Paper IV).

1.5. Novelty and significance of the study

Many research focus on automatic sampling method, which is not always feasible and/or affordable. The inclusion of site selection, best practied manual sampling and integration of manual and automatic sampling approaches are found to be applicable and effective at limited resources.

The separation of roads and roofs in GIS, based on the connectivity to storm drainage and their impact analysis due to build up and wash off components, is rarely found in previous studies. The results suggest that the effective treatment measures should focus on the runoff from these land uses. The resulting impervious percentage due to mixed land use in large catchment basins was found to be low.

The estimations from grab sampling have greater uncertainty. The model application is a useful tool to validate the data. When applying grab sampling, the samples need to be taken for medium and large events within 6 hours of storm commencement to best represent the storms and provide near accurate results.

1.6. Outline of Thesis

This thesis is based on four appended papers. The thesis starts with a brief introduction of the study where the problems are stated that give an overview of the context of the study. Chapter 2 contains a comprehensive literature review, which includes a brief history on Tallinn stormwater managment, recent compliance criteria, sources of pollutants, previous studies related to Tallinn stormwater, monitoring programmes and modeling. Chapter 3 gives a brief description of the study site, data resources, methods and tools used in the research, while in Chapter 4 the results from the four papers are summarised, the findings in relation to the literature, overlooked limitations and suggestions for future work are discussed. The conclusions and recommendations of the research presented in this thesis are presented in Chapter 5.

2. LITERATURE REVIEW

2.1. Brief history of stormwater management in Tallinn

In the history of water and sewerage managment in Estonia, the first mentioned sewer lines were the underground wooden pipes in the old town that date back to 1422, which were used for almost 400 years (Juuti & Katko, 2005). In the 17th century, sewers were constructed in most of the streets in the old town with limestone canals in a few streets. In 1843, the wooden pipes were replaced with cast iron pipes. The territory of the city expanded over the years, and the sewerage work began in the suburbs at the cost of owners and city council. Natural waterbodies and drain ditches were used for transporting the sewerage according to gravity. From 1881, Härjapea river was used as sewage collector. For around a century, this river area was the most densely populated area. The river had turned into an open smelly sewer and it was eventually covered over with wooden planks after 1923. The combined sewer lines expanded from 46 km in 1905 to 130 km in 1937, discharging to Tallinn and Kopli bays. In 1945, the sanitary situation of Tallinn's sewerage was unsatisfactory. Even Kopli Bay was closed for swimming. Extensive sedimentation, flooding, economic crisis due to World War II, the construction of new houses and industries had worsened the situation. At the beginning of the 20th century, the network was divided into 8 independent systems, two of which flowed into Kopli Bay and six into Tallinn Bay, but before this in 1945, there used to be 46 sewer outlets to the Tallinn and Kopli bays, plus outlets from the factories. Pipes became norrower to growing amount of wastewater. Separate sewer systems were built in new residential areas and stormwater was directed to Kopli Bay (Hanni, 1999). The new system was planned to consist of two main sewers and a main pumping station in Paljassaare. All the wastewater was to be treated in mechanical treatment facilities and then led to the sea. Construction work started, and in 1962 a main sewer was completed to serve the western part of town. Meanwhile, it became evident that the system was inefficient, and the increase in wastewater demanded an updated plan.

In 1966, a new centralised sewerage system was designed in the city development strategy based on future needs. With the establishment of Tallinn water works and sewerage management (later AS Tallinna Vesi) in 1967, this system was connected from newly constructed sewers in the central and eastern part of Tallinn, Õismäe residential area and Lasnamäe area from 1968 to 1972. By the end of 1970s, two collector sewers, the main pumping station and a sea outlet were completed. The mechanical treatment plant became operational in 1980 and its biological treatment facilities in 1994. The biological wastewater treatment plant began to operate in 1994. The treated wastewater is discharged into the Gulf of Finland via 3 km long sea outlet pipes (Hanni, 1999).

Stormwater related pollution problems arose in the 1970s when western countries started to construct wastewater treatment plants. Since the 1980s, there have been several changes in the legal documents that have also affected pollution levels. One of the first international recommendations (Recommendation No. 5/1) concerning stormwater transported contamination was adopted by HECOM at its fifth meeting in 1984. This recommendation mainly dealt with limiting oil products (hydrocarbons) until the second recommendation (Recommendation No. 17/7) in 1996 for controlling suspended solids was introduced. In 2000, these two recommendations were merged into Recommendation No. 23/5. A later recommendation was upgraded and updated and it has been valid since 2002, where attention has been paid to reduce volume through local infiltration system, prevent the deterioration of quality controlling water from the streets with heavy traffic and heavily polluted area and minimise the effect of first flush. It was also identified that the control through combined sewer overflows and the number of overflows prevents the amount of pollution.

The principal components of national water legislation were introduced in the early 1990s after gaining independence from Soviet era, and they were elaborated in the first phase of Estonian Water Act, which the Estonian Parliament adopted on 11 May 1994. On the basis of the Water Act, requirements related to the discharge of pollutants into soil or water were adopted by government (RTI, 2001), where the water protection measures followed on from HELCOM recommendations. Since the early 2000s, these components have been modified to incorporate EU WFD requirements since accession to the European Union.

To meet the requirements of the European Union and to apply the HELCOM recommendation, Tallinn City Environment Department has been reconstructing and expanding the networks as well as centralising the sewerage system. AS Tallinna Vesi, a special water permit owner that became a stock company in 1997, has been taking care of stormwater since 2001. It is responsible for the collection, discharge and treatment of stormwater. This century, there has been extensive stormwater and sewerage network construction and renovation in Tallinn, which lasted almost a decade (Figure 2.1.). Tallinn's public sewerage system now comprises 1,104 km of sewerage networks, 478 km of stomwater networks and 174 sewerage pumping stations. According to AS Tallinna Vesi (2014), 97 % of the Tallinn area was connected to the public sewerage system by 2006 and, in collaboration with the City of Tallinn, the company had covered 99 % with the public sewerage network by the end of 2010. In addition, the City of Tallinn has initiated street cleaning methods in most of the areas in the past few years, along with the installation of sand and oil filters on major roads and car parks (RTI, 2013b; Tallinna Vesi, 2014).

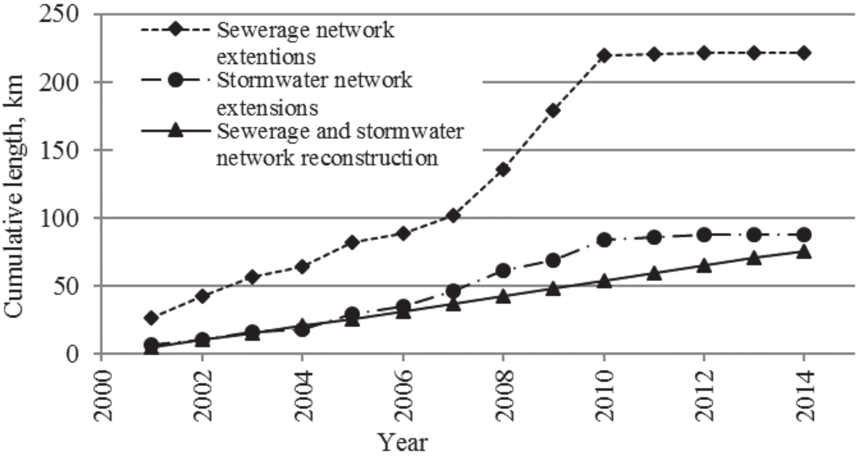


Figure 2.1. *Stormwater and sewerage network extension and reconstruction in Tallinn.*

Stormwater management technolgies are not yet well practiced in Tallinn city. The first example is the construction of the stormwater drainage system of Ülemiste junction, which is designed to reduce the stormwater impact on the sewerage pipelines and was completed in 2012. In the course of construction, water was directed to the historical Kadriorg Park, where it feeds the park's canals. The historical circular canal with cascades in front of Kadriorg Palace was reconstructed and stormwater facilities, a cascade with five levels, a pond and stormwater outlet into the sea were built in the course of the reconstruction work (TCO, 2016). The second is the renewal of a section of Lepiku watercourse situated in Tallinn Botanical garden in order to reduce the impact on River Pirita. It is a small natural drainage watercourse where width and depth were constructed to vary such that the water flow retains the improving sedimentation of suspended particles. Plants were also added along the course both on the bottom and sides as to function a natural barriers and nitrogen fixation. It is a good example to demostrate that the water elements can diversify nature and bring recreational values to the area instead of directing the water into a pipe system (CITYWATER, 2016). The third is green roofs, which is applied in some houses in Tallinn. Quality reduction through green roofs in Estonia is sceptical (Teemusk & Mander, 2011), though in recent years the practice of green roofs on public and private houses has begun. Rain water harvesting is also not common in Tallinn except one in an office building, which has been used since 2014. Beside these, trenches and natural drain ditches have traditionally been built alongside the roads.

In recent years, Tallinn has seen more problems associated with stormwater drainage as roads, streets and real estate flood during periods of heavy rain and snow melting. As already mentioned, a list of activities about stormwater managment were planned in the Tallinn Development Plan 2014–2020 (Tallinn City Council Regulation no. 29, 13.06.2013) (RTI, 2013b), Tallinn water supply and sewerage development plan 2010-2021(Tallinn City Council Regulation no. 54, 18.11.2010) and Tallinn Stormwater Strategy until 2030 (Tallinn City Council Regulation no. 18, 19.06.2012) (RTI, 2012). The aim is to improve the state of the urban environment from one of the perpectives that includes stormwater managment. The main activities concerning stormwater are: minimise stormwater volume and pollution using stormwater as a resource, regulating stormwater flows, treating near natural stormwater managment solution, reconstruction and improvement approach to the combined system, establishment of a proper stormwater monitoring programme, drainage solution through basin based model development, etc. The enforcing national acts for implementing and montoring these activies are: Estonian Water Act, Public Water Supply and Sewerage Act, Local Government Organisation Act, Environmental Monitoring Act. The updated regulations are: Gov. Reg. No. 99 and regulation for hazardous pollution stated in national Water Act. The international enforcing regulations are EU directives-Urban Wastewater Directive (91/271/EEC) and Flood Directive 2007/60/EC, and HELCOM Recommendations- No. 23/05 and no. 28E/5 (adopted 15 Nov 2007 about urban wastewater treatment and nutrients disposal).

2.2. Stormwater compliance criteria:

According to Estonian Gov. Reg. No. 99, stormwater discharges to the waterbodies and soil should not exceed the limit values that apply to wastewater under the pollution level for 2000−9999 PE, with the exception of suspended solids (SS), which should not exceed 40 mg/l, and hydrocarbon oil content, which should not exceed 5 mg/l (RTI, 2013a). The limit values are presented in Table 2.1. If the stormwater pollution indicators do not meet the characteristics specified in Table 2.1, then it needs purification before discharging to the recipient. In the case of combined sewers, the overflows should be designed in such a way that the wastewater should be diluted as one part of the effluent wastewater with at least four parts of stormwater.

***Table 2.1** Limit values of stormwater pollution outlet*

Parameters	Limit values
pH	6−9
Suspended solids, mg/l	40
BOD5, mgO/l	15
Total Nitrogen, mgN/l	45
Total Phosphorus, mgP/l	1
hydrocarbon, mg/l	5

According to Minister of Environment Regulation No 44 of 28 July 2009 "Procedure for establishing parameters of surface waterbodies and their lists, limit of classes, state of the classes corresponding to the values of quality indicators and the procedures for determining the status of classes", the surface waterbodies can be evaluated as very good to very bad status as in Table 2.2 based on the values of quality indicators that lie within the limits of classes (RTI, 2010).

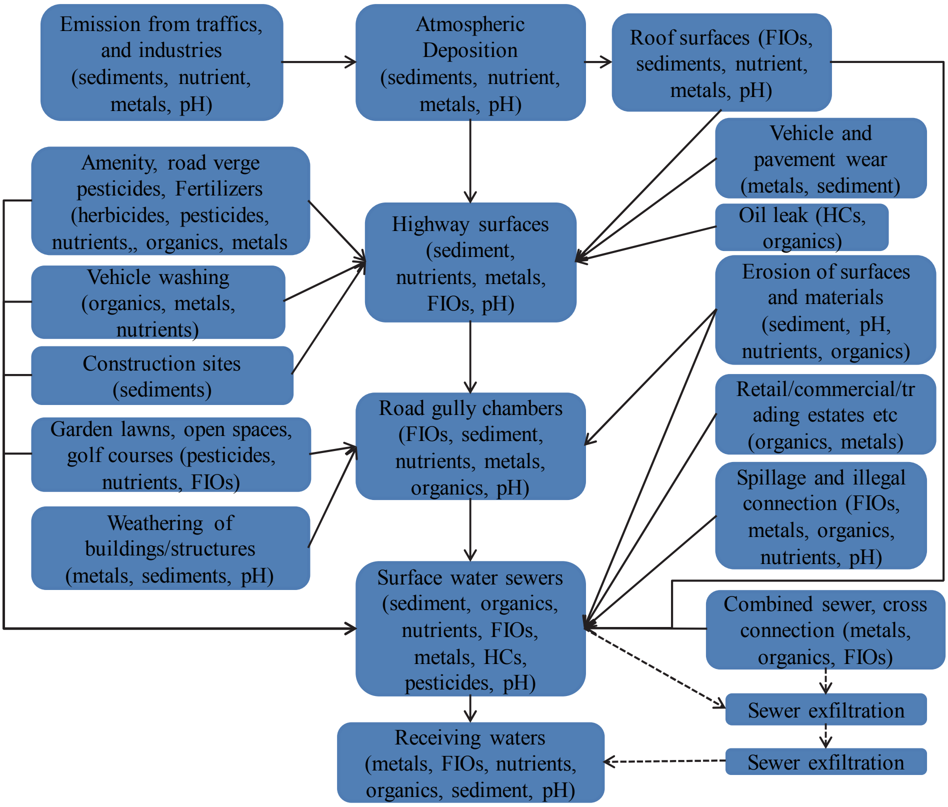
***Table 2.2** Watercourses physicochemical parameters and limits of classes for types I, II, III B*

Attributes		Unit	Class				
			very good	good	weak	bad	very bad
Dissolved O_2	10 % collateralisation	% saturation	>70	70-60	<60-50	<50-40	<40
BOD_5	Arithmetic mean	mgO/l	<1.8	1.8-3.0	>3.0-4.0	>4.0-5.0	>5.0
TN	Arithmetic mean	mg/l	<1.5	1.5-3.0	>3.0-6.0	>6.0-8.0	>8.0
TP	Arithmetic mean	mg/l	<0.05	0.05-0.08	>0.08-0.1	>0.1-0.12	>0.12
NH_4^+	90 % collateralisation	mgN/l	<0.10	0.10-0.30	>0.30-0.45	>0.45-0.60	>0.60
pH	10 % collateralisation	pH unit	6-9	6-9	6-9	6-9	<6-9>

The European Union, as well as Estonia, has restricted microbiological parameters exceeding 1000 cfu/100ml Escherichia Coli (E. coli) and 400 cfu/100ml Enterococci for good bathing water quality (EU, 2006; RTI, 2008).

2.3. Common stormwater pollutants and their sources

Stormwater pollutants originate from different sources during the course from runoff generation to the end to the receiving water body (Figure 2.2). Runoff generation varies greatly between different rainfall events and locations, as a result of dry and wet weather conditions such as rainfall intensity and duration, seasonal variation and antecedent dry days (ADD) (Donald W. Glenn & Sansalone, 2002). When precipitation occurs, it washes off the built up of pollutants from the atmosphere and the urban surfaces. While transporting, it carries the accumulated deposits in sewers. In addition, the subsurface flow can add up the pollutants. The common urban stormwater pollutant groups are sediments, heavy metals, organics, nutrients and micro-organisms coming from dust and dirt accumulation, vehicular wear, traffic and industries emissions, weathering of roofs and surfaces, construction and commercial activities, highway activities, plant/leaf and litter debris, animal/bird excreta, leakage and spillage (Göbel et al, 2007; Lundy et al, 2012). The illicit and cross connection of sewers as well as exfiltration in sewers and ground water intrusion (shown by dotted arrow in **Error! Reference source not found.**) add pollutants to the receiving waterbody. In **Error! Reference source not found.**, highways and road gully chambers function as both sinks and reservoirs. Because some temporary storage of water can occur at these stages, it creates time for pollutant transformation and, ultimately, the pollutants will be different than the one starting at the sources (Lundy et al, 2012). Being the potential sinks, they can be taken as the principal source in a conveyance system, even though the most effective control measures must be applied at the original source in order to minimise receiving water risks. Another significant factor is the meteorological conditions. The accumulation and removal of pollutants differ considerably between winter and non-winter conditions because the pollutants accumulate as a snowpack during long period of negative temperature, which generally melts within short time period resulting in peak concentration in runoff (Westerlund et al, 2003; Sillanpää, 2013). Early snowmelt fraction in a first flush includes ions and water-soluble substances while later fraction of snowmelt mostly contains particle bound pollutants (Viklander, 1997; Sillanpää, 2013).



FIOs - Faecal Indicator Organisms; HCs - Hydrocarbons

***Figure 2.2** Common stormwater pollutants and their sources (modified from (Lundy et al, 2012; Revitt et al, 2014))*

Table 2.3 *Pollutant magnitude in stormwater studies in European and Estonia's neighboring countries*

Para-meter	Event mean concentrations (EMCs)[1] based on European data										EMC	Range and average		
	Residential		Commercial	Indu-strial	Roads		Roof	Gully Liquor	Miscon-nection	Urban amenity	Finland[2]	Vilnius, Lithuania[3,4]	Poznań, Poland[5]	Scandinavian countries[6,7]
	High density	Low density			High density	Low density								
TSS (mg/l)	55–1568	10–290	12–270	50–2582	110–5700	11–5400	12.3–216	15–840	300–511	na	2.8 – 975	4–800 (38—200)	1.8–736 (16.9—55.3)	50–200
BOD (mg/l)	2–17	0–4	5–22	8–23	12–32	2–27	2.8–8.1	68–241	200–260	na	na	0.6–300[c] (4.7—30)	1.17–25.11[d] (4.7—7.5)	na
COD (mg/l)	na	na	na	na	na	na	na	na	na	na	80 – 200	13–1400[a]	na	10–200
Hydrocarbons (µg/l)														
HC	0.67–25.0	0.89–4.5	3.3–22	1.7–20	7.5–400	2.8–31	na	na	na	na	na	<0.05–21.4 (1.3– 2.4)	na	na
PAH	na	na	0.35 – 0.6	na	0.03–6	1–3.5	na	na	na	na	na	na	na	na
Nutrients (mg/l)														
T N	0–6		na	na	0–4	na	na	0.7–1.39	na	na	0.3–15.8	na	0.69–14.6 (2.7 –5.7)	0.6–2.1
NH_4	0.4–3.8		0.2–4.6	0.2–1.1	na	na	0.4–3.8	na	5	na	na	na	0.38–7.36	na
T P	na	na	na	na	na	na	na	na	39	0.02–14.3	0.02–2.5	na	0.02–0.57 (0.12–0.22)	0.1–0.35
Metals (µg/l)														
Pb	0–140		na	na	3–2410	10–15	1–30	100–850	na	na	na	100–3600	0–85.10	10–300
Cd	0–5		na	na	0.3–13	0.2–0.5	na	na	na	na	na	na	0–1.45	0.3–4
Zn	150		na	na	53–3550	53–410	na	na	na	na	na	900–12400	0–7820	50–400
Cu	na	na	na	na	na	na	na	na	na	na	na	400–2000	0.21–326	10–100
Ni	na	na	2 – 493	na	4–70	na	na	na	na	na	na	200–800	0.03–31.7	na
FIOs: E. coli (MPN/100 ml)	na	na	na	na	40–10E6	na	40–10E6	na	10E3–10E6	na	na	na	na	na

TSS=Total suspended solids; BOD= Biological Oxygen demand; COD=Chemical oxygen demand; HC = hydrocarbons; PAH = polyaromatic hydrocarbons; FIOs= Feacal Indicator organisms; na=not available; NH_4=Ammonia; 1 – (Revitt et al, 2014); 2 - (Sillanpää, 2013); 3 - (Karlavičienė et al, 2008; Mancinelli et al, 2015) 4 - (Vasarevičius et al, 2010); 5 - (Baralkiewicz et al, 2014); 6 - (Nordeidet et al, 2004; Modaresi et al, 2010); 7 - (Nordeidet et al, 2004)

Table 2.3 shows the range of pollutants frequently reported to be present in the urban runoff of European countries and those of Estonia's neighbours. Data recorded in research are in two forms: one is event mean concentration (EMC) and the other is instantaneous concentration, usually from grab sampling. The first type of data, i.e. EMC, considers the mean concentration of each single event to define a non-extreme event and applied to estimate site mean concentrations (SMCs)/ annual mass loads. The second type of data is to compare with consent limits or environmental quality standard (EQS) such as the maximum allowable concentration and annual average, to protect against short term or acute exposure and long term or chronic effects. The pollutant quality and quantity vary considerably between sites due to land use type and intensity as well as the drainage system, such as illegal connection, exfiltration of sewers, etc., (Göbel et al, 2007; Lundy et al, 2012) as in Table 2.3. For instance, high traffic densities on highways, motorways and parking areas can increase the rate of road surface abrasion, tyre abrasion, combustion emission and drip losses. Not only suspended solids but also heavy metals and hydrocarbons are emitted in high quantities from these road surfaces.

Pollutants in urban runoff are found in both dissolved and particulate matters. However, the majority of pollutants are associated with a particulate phase. Suspended solids are important carriers of both metals and organic pollutants, and are often used as a universal water quality parameter (Björklund, 2011; Selbig et al, 2013).

2.4. Previous studies related to Tallinn stormwater

Stormwater in Tallinn has been the focus of attention since the early 1990s after the Paljassaare wastewater treatment plant became operational and the effluent became clean enough to discharge deep into the sea (Pauklin et al, 2005-2011). The regular monitoring of the stormwater condition in Tallinn was then started. Tallinn Environment Department commissioned the Environmental Research Centre to conduct monitoring until 2011, AS Tallinna Vesi and Tallinn University of Technology, Department of Environmental Engineering for 2012-2014 and the Estonian, Latvian and Lithuanian Environmental group for 2015. Over the last 15 years, the impact of stormwater on the receiving waterbodies were investigated and they came to the conclusion that the pollutants in stormwater systems have decreased, thereby improving the quality of stormwater considerably as in Table 2.4 (Pauklin et al, 2005-2011; TCO, 2016). The limit concentration of hydrocarbon oil products and heavy metals has not been exceeded in the last 10 years.

Nevertheless, the degredation of coastal waters is prevalent and pollutants discharge from stormwater have a considerable contribution, especially in Tallinn Bay (Erm et al, 2014) and Kopli Bay (TCG, 2015). The study conducted in 2009 for the ecological status of coastal water in Tallinn city showed moderate ecological status in two of the three studied waterbodies of Tallinn Bay (Miiduranna, Pirita) and one in Paljassaare Bay; however, it was bad in one waterbody of Tallinn Bay (Kalaranna-Russalka) and one of Kopli Bay (Stroomi)(TCG, 2015). Yet, the long-term improvement trends were observed in the Paljassaare and Miiduranna sea areas, the study suggested that the stormwater has a potential impact on water transparency and depletion of the oxygen level. The foul smell in Tallinn Bay is still a problem. The cause was investigated by the Estonian Marine Institute and the University of Tartu, and it was found that the concentration of phosphorus was a limiting factor in enhancing algal growth, accumulation and decaying in the shallow coastal water on the beach where the concentration of hydrogen sulphide (H_2S) and the unpleasant odour are present (Erm et al, 2014). From studies by the Estonian Environmental Research Centre (Pauklin et al, 2005-2011) it was determined that the Kadriorg outlet of Tallinn Bay receives half of the amount of nitrogen delivered to the bay by stormwater outlets. In 2012, Estonian Ministry of Environment initiated the study to clarify factors corresponding to spreading of algae on the coastal waters of Kadriorg-Maarjamae area and to offer solutions for the problem. The Marine Systems Institute at Tallinn University of Technology was involved. They sampled 100 grab samples from two rivers and stormwater outlets, 150 seawater and 142 sediment samples from coastal area. They found that nutrients influx from stormwater outlets also have a considerable contribution in biomass production. In rainy or summer periods, the nutrients influx, and in particular the nitrogen concentration, is severe and can play a major role in algal bloom (Erm et al, 2014).

Table 2.4 *Pollution loads of the two largest stormwater outlets in Tallinn (Lauluväljak and Rocca al Mare) from 2004-2014*

Indicator	Lauluväljak					Rocca al Mare				
	2004-2009	2011	2012	2013	2014	2004-2009	2011	2012	2013	2014
Suspended solids, t/y	24	17.1	19.8	48.5	19.8	126	236	38.8	82.0	37.2
BOD_7, t/y	10.3	10.5	11.6	8.5	5.1	33.7	40.0	12.1	11.1	17.9
TN, tN/y	13.6	21.4	20.8	8.2	6.9	11.1	13.4	9.8	6.2	5.2
TP, tP/y	0.403	2.03	1.07	0.57	0.38	2.19	2.26	0.96	0.76	0.61

source: adapted from TCO, 2016.

There are few studies on quality dynamics for large catchment basins. In Estonia, the modeling of stormwater is rarely found. Hood et al.(2007) used the SWMM model to estimate flow and pollution load of moderate size of the Tallinn sub-catchment. They found the modelled runoff and pollution loads (TSS, TN and TP) for 2004 from the Lasnamäe basin were higher than the estimated amount by the Estonian Environmental Research Centre and AS Tallinna Vesi. The predictive capabilities were not evaluated and unclear about the uncertianty. The six small sub-catchments with distinctive land use (transportation, residential and commercial) in Tallinn were analysed for runoff and suspended solids by Koppel et al. (2014). They identified a varying runoff coefficient minimum in June and maximum in September, as it ranged from 0.41 to 1 for commercial areas and 0.19 to 0.77 for residential areas. They suggested the suspended solids peak at the start of water flow. However, the correlation between the modelled and measured flow rates was weak in their analysis. Both studies used rainfall data from Harku station, which is almost 5−7 km away from the studied sites, which increases uncertainties in the results. The runoff dynamics of mixed land use can be different from single land use as they provide a resultant runoff coefficient that is different from individual land use (Lee et al, 2009). There is also a room to look at the impact of directly connected impervious areas. Lee and Heaney (2003) modeled the hydrologic performance of DCIA and reported that DCIA is the main contributing area of runoff and has the most pronounced effect on urban hydrology. DCIA or the connectivity to the urban area at the catchment scale influences the hydrologic response (Yang et al, 2011; Burns et al, 2015) .

2.5. Review on stormwater monitoring

Stormwater monitoring is a quantitative approach for evaluation of a stormwater management programme (US EPA, 2009). There are many guidelines and procedures proposed in documents for stormwater monitoring by national, regional or local governments. For example, the Australian and New Zealand Environment and Conservation Council (ANZECC) and the Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ) (ANZECC & ARMCANZ, 2000) have preapared Australian Guidelines for Water Quality Monitoring and Reporting; the US EPA have developed the NPDES Storm Water Sampling Guidance Document and Industrial Stormwater Monitoring and Sampling Guide (US EPA, 2009), Geosyntec Consultants and Wright Water Engineers (GC & WWE, 2009) have released Urban Stormwater BMP Performance Monitoring, etc. The collection of reasonably accurate data is one of the most challenging aspects of stormwater monitoring (GC & WWE, 2009; US EPA, 2009). Many sampling programmes in the guidelines have not been designed precisely with a deductive consideration of the objectives and sampling requirements (Bertrand-Krajewski et al, 2000; Fletcher & Deletic, 2007). In this study, the sampling approaches are briefly reviewed, but the extensive review was performed in Paper III.

In previous research, approaches for appropriate site selection, selecting minimum parameters and choosing options based on the degree of required certainty and cost are rarely given any attention. The variation in stormwater quality and quantity is large between the catchments and even in a single catchment. The monitoring of numerous sites is resource costly. The proper method of site selection limits the potential sites, reduces cost and increases accuracy (Lee et al, 2007; Langeveld et al, 2014). It is also important to select the most important few parameters that will ensure broad-spectrum testing and comparable datasets (Ingvertsen et al, 2011). Several studies have reported potential organic and inorganic parameters (Makepeace et al, 1995; Göbel et al, 2007; Madrid & Zayas, 2007; Ingvertsen et al, 2011; Lundy et al, 2012), physicochemical parameters (Paschke, 2003; Göbel et al, 2007; Madrid & Zayas, 2007) and priority pollutants (Eriksson et al, 2005; Zgheib et al, 2008; Gasperi et al, 2012; Kegley et al, 2014), which are either harmful to human or aquatic life and/or both. The approach of sampling surrogate parameters assists in minimising the number of resource intensive and time consuming sampling parameters (Settle et al, 2007; Miguntanna et al, 2010).

Uncertainty in discharge measurement comprises 7 to 23 % and sample collection comprises 14 to 36 % (Harmel et al, 2009), and it can be reduced significantly through a proper sampling programme. Uncertainty in discharge measurement is built up through the type of methods used, type of equipment and staff skills (Sauer & Meyer, 1992; Slade, 2004; McIntyre & Marshall, 2008; Sauer & Turnipseed, 2010; Nord et al, 2014). For example, the velocity area method to construct stage discharge relationship has a lower error factor of 2−20 % than Manning's Equation method which has an error factor of 15−35 % (Sauer & Meyer, 1992). The illustrations of different methods of discharge measurement are found in many hydrology books, manuals and USGS documents (Buchanan & Somers, 1968; Brakensiek et al, 1979; Maidment, 1993). In the sample collection system, samples can be taken manually and/or automatically. There are practical guidelines that have been illustrated for automatic sampling (Harmel et al, 2006b; David & Daren, 2014). Though automatic sampling is the most common practice producing higher accuracy, it is not always feasible and/or affordable. Grab sampling has been favoured when performing long-term sampling (Leecaster et al, 2002; Fletcher & Deletic, 2007; Lee et al, 2007) and measuring certain toxic elements and oil/grease compounds (Khan et al, 2006; Lee et al, 2007). Moreover, uncertainty in samples collection differs whether it is taken as single or integrated (Taylor et al, 2005; Harmel et al, 2006a; McCarthy et al, 2008; McCarthy et al, 2009), flow or volume or time weighted and composite or discrete samples (Miller et al, 2000; Harmel et al, 2002; King & Harmel, 2003; Harmel et al, 2006b).

Nevertheless, the required level of uncertainty is often unclear; therefore, the appropriate frequency and timing of sampling is not well understood (Leecaster et al, 2002; Fletcher & Deletic, 2007). For some time, several studies have been carried out to provide effective time of sampling (Harmel et al, 2002; Harmel et al, 2006a), frequency of sampling (Leecaster et al, 2002; King & Harmel, 2003; Harmel & King, 2005; Harmel et al, 2006a; Khan et al, 2006; Lee et al, 2007) and number of storms to be sampled (Leecaster et al, 2002; May & Sivakumar, 2009; Maniquiz-Redillas et al, 2013). It is essential to periodically refine frequency, timing and sampling methods to attain representative, quality and high certainty data (Fletcher & Deletic, 2007).

The monitoring programme in Estonia is based on Gov. Reg. No. 99 (RTI, 2013a). The limit values are set for parameters and stormwater discharges should not exceed that limit. The sampling method is specified as time or flow proportional sampling where samples are taken after 30 min from the start of runoff at every 30 min interval for at least 2 hours or until the runoff stabilises. The frequency of this sampling must be at least once per year and not emphasised to take frequently. Runoff calculation should be based on the standard EVS 848 or equivalent standards. The regulation is unclear about the kind of concentration to compare with limit values because flow or time proportional samples are mainly aimed for EMCs and peak concentrations. On the one hand, the number of storm events needs to be specified because EMCs depends on the intensity and duration of storm events. On the other hand, if peak concentrations are compared with limit values, they can frequently exceed e.g. SS and BOD are found several times higher than limit values. In the case of the high fluctuation of flow and pollutants, the automatic sampling system is favourable. Indeed, these issues need to be addressed in the Tallinn stormwater strategy where one of the aims is to establish a proper monitoring programme (RTI, 2012).

2.6. Review on stormwater modeling

A wide variety of models addressing stormwater quantity and quality have been developed. The review on the stormwater models by Elliot and Trowsdale (2007) and Jayasooriya and Ng (2014) found that EPA SWMM has better performance in simulating stormwater quantity and quatity. SWMM has reasonable accuracy when model outcomes are calibrated and validated (Jayasooriya & Ng, 2014). It is a comprehensive hydraulic and hydrological model used for a single and continuous event (Rossman, 2010). Its conceptual model is built with four environmental compartments. The first compartment works with atmospheric objects e.g. rain gauges, temperature, wind speed, etc, which accounts for precipitation and pollutants from air. The second compartment is based on land surface e.g. sub-catchments, which models runoff and pollutants generation. The third compartment is related to ground water objects e.g aquifers, which receives infiltration from land surfaces and provides input to the fourth compartment called transport compartment. This compartment consists of objects such as pipes, channels, etc. to route flow from the runoff source. SWMM has broad applicability for simulating runoff and quality dynamics e.g. hydrology assessment for pre/post development condition (Jang et al, 2007), pollutant washoff water quality analysis (Temprano et al, 2006; Lee et al, 2010), combined sewer overflow modelling and assessment (Zhang & Li, 2015), flood forecasting (Han et al, 2014), and stormwater treatment facilities modeling and assessment (Aad et al, 2010; Burszta-Adamiak & Mrowiec, 2013). It is free software available with a graphical user interface. As it is a physical based deterministic model, it requires various input data that need to be calibrated and validated before use as a predictive model.

For calibration and validation, manual or automatic techniques can be used. In manual calibration, the optimised set is determined through manual trial and error method, whereby one or more input parameters will be changed and a measure of goodness of fit between model results and calibration dataset is noted. Manual calibration can be effective if approached systematically (e.g., stratified sampling approaches) (McKay et al, 1979), and when the number of parameters to be calibrated is limited. Many studies have applied this technique for calibration and validation to assess runoff and loads (Tsihrintzis & Hamid, 1998; Temprano et al, 2006; Nazahiyah et al, 2007; Tan et al, 2008; Lee et al, 2010; Chow et al, 2012; Mancipe-Munoz et al, 2014). However, most of them are based on small catchment basins. In a large catchment, the mixed land use produces a higher variability in stormwater quality, as there will be a high interspersion of various land use types (Lee et al, 2009). Tan et al. (2008) and Mancipe-Munoz et al. (2014) worked on comparatively large urban catchments but mainly focused on runoff calibration, though they worked for continuous events too. There are few studies on quality calibration for the large catchment basins. Moreover, in our knowledge with a local context, only a basin in Tallinn of moderate size was modelled by Hood et al. (2007), but the calibration and validation is not explicitly performed for model predictability.

3. MATERIAL AND METHODS

In this chapter, the complete material and methods applied in the study will be described. Familiarising the study site, details of data sources, sampling methods and the statistical methods for assessing the status and trends of stormwater in Tallinn will be given an overview. Further, discussing the review process for sampling approaches and the methods used in model development will be illustrated.

3.1. Study Site Description

Tallinn, the capital of Estonia, is situated in the north-western part of Estonia on the shores of the Gulf of Finland. It has a total area of 156 sq. km where approximately 32 % of population is centred. The climate is humid continental with warm to mild hot summers and cold snowy winters. The average air temperature between 1961 and 2010 ranges from -5.9 to -1.0 in January and 12.7 to 21.9 in July (EWS, 2015). Total annual rainfall is 704 mm and average monthly rainfall varies from 32 mm in April to 86 mm in August. Snow cover usually lasts from mid-December to late March. The average rainfall is 550–750 mm and the mean runoff is 280–290 mm per year. Most of the land in Tallinn is urbanised, with impervious areas forming about 50 % of the total area. There are 66 stormwater outlets (EELIS, 2015). Among them, 47 outlets discharge to

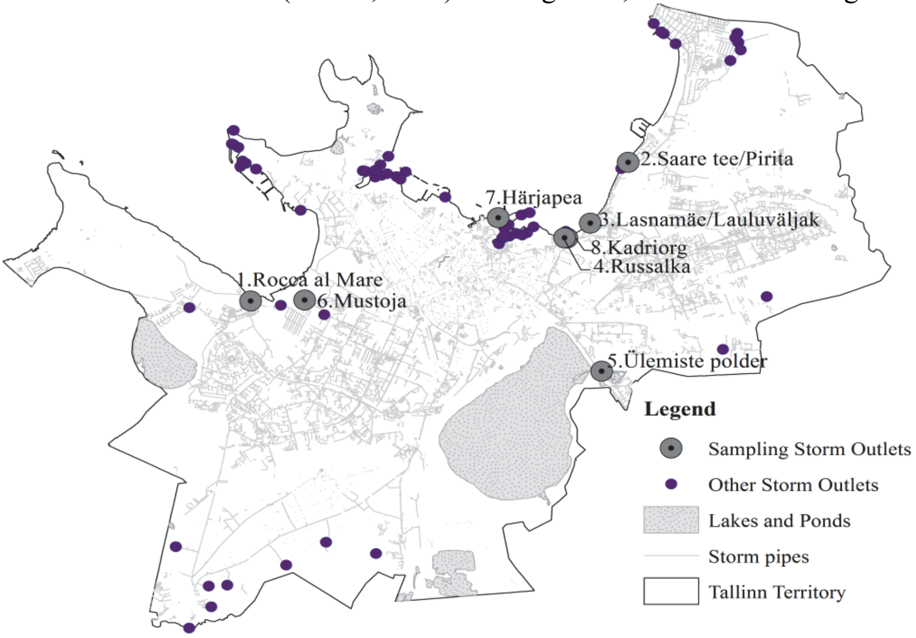


Figure 3.1 *Stormwater outlets in Tallinn*

Table 3.1 *Area coverage of most important catchment basins and their characteristics*

Basin	Area, ha	% Coverage	Receiving water body	Characteristics
Rocca al Mare	816	21.3	Kopli Bay	storm and surpluswater from the block houses areas, mostly, from pools in zoo during water exchange, increase in impervious areas is noticed in the catchment.
Pirita/Saare tee	156	4.1	Tallinn Bay	storm and drainage waters from private house area, collected via open ditches and Varsaallika spring (basin 1.6 km^2), sewage discharges from the private houses area can occur
Lasnamäe/ Lauluväljak	961	25.1	Tallinn Bay	mostly high density area with impervious area one third of total area. Runoff collected from residential and industrial. sewage discharges can occur from this area
Russalka	734	19.1	Tallinn Bay	consist mostly from the Ülemiste polder storm and drainage waters and Lake Ülemiste surplus water after heavy and continous rains, and during snowmelt period.
Ülemiste polder			Tallinn Bay	storm and drainage waters from industrial district and private houses area, airport treated stormwater and runways stormwaters, Ülemiste polder drainage water
Mustoja	1128	29.4	Kopli Bay	storm and drainage waters mostly from private houses area, block houses and industrial district collected via ditches, open channels and pipes into the Mustoja River, increase in impervious areas is noticed in the catchment, sewage discharges from one of the private houses area can occur.
Härjapea	~40	~1	Tallinn Bay	includes the areas of Põhjaväila and the streets of Lootsi and Ahtri along with suburbs of the central city. The Old Town with its historic buildings, medieval stonewalls, churches, stone pavements and old houses have possibility of partial discharge to this outlet.
Total	**3835**			

the coastal sea. The major outlets that discharge to Tallinn Bay are Härjapea, Saare tee/Pirita, Lasnamäe, Russalka, Ülemiste Polder and to Kopli Bay are Rocca al Mare and Mustoja as shown in Figure 3.1. Their catchment characteristics along with the coverage area are presented in Table 3.1. The area of the stormwater system of Tallinn is about 6,500 hectares and the length of the stormwater pipeline was 478 km in 2014 (Tallinna Vesi, 2014). Stormwater from residential and industrial areas is either diverted to municipal wastewater treatment plants (WWTPs) and treated with sewage or is collected in a separate stormwater system and mainly discharged to waterbodies without any treatment.

Altogether, these 7 outlets cover a total approximate area of 3,900 ha. Among them, Mustoja basin is the largest and covers almost 30 % of the total area.

Mustoja is the pilot study basin for stormwater modeling and approximately 10.24 km^2 of the territory was covered in simulation. Most of the area spread over the Kristiine and Mustamäe districts in the upstream side. Runoff flows mainly through underground pipe networks and ditches to the downstream natural channel where three pipes under Marja, Haabersti and Mustjõe streets intersect. Finally, this water is discharged to Kopli beach and into the Baltic sea. The land use within the catchment is mainly residential covered with private and apartment buildings in the upstream side. Industrial and commercial areas are dominant features in the downstream side within the catchment.

3.2. Data sources and sampling strategy

For this study, data from four sources have been obtained (Figure 3.2). The first source of data (S1) is monitoring reports from Pauklin et al. (2005–2011) for the years 2005 and 2008–2011. In this monitoring system, grab samples were collected 4–6 times a year from the stormwater outlets by the Estonian Environmental Research Centre. The data was measured only once in 2010. The second source (S2) is monitored data provided by AS Tallinna Vesi, a special water permit owner that has measured samples each month from 1996 to 2014 in 6 outlets: Härjapea, Lasnamäe/Lauluväljak, Pirita/Saare tee, Mustoja, Rocca al Mare and Russalka. Besides these, one other outlet is Kadriorg, which has only two years of data and is excluded for analysis. Six parameters – pH, SS, TN, TP, BOD$_7$ and HC – were measured with grab sampling. The third source (S3) consists of samples measured by both the department of Environmental Engineering of Tallinn University of Technology (TUT) and AS Tallinna Vesi for the period 2012–2014 in six outlets excluding Härjapea and Kadriorg, though Ülemiste polder was included. The samples were tested for parameters such as dissolved oxygen, conductivity, pH, temperature, SS, TN, TP, BOD$_7$, HC, salmonella, E. coli and Enterococci using analytical methods based on ISO and Estonian water quality standards (listed in Paper II). All of these are competent bodies according to EN ISO/IEC 17025:2005 for conducting tests in the field of water analysis (accreditation scope on the Estonian Accreditation Centre). The sampling procedure was in line with Estonian Environment Minister Regulation "Sampling methodology" as stated in the Water Act. EVS-EN 25667-2, EVS-EN ISO 5667-3:2012 or any equivalent internationally recognised standard should be followed. The fourth source (S4) is monitored data from the department of Environmental Engineering of Tallinn University of Technology.

At the Mustoja basin outlet, TUT installed a water level measurement gauge to form a discharge-rating curve. The time interval sampling approach, sampling approach 1 (SA1), was used to collect the samples during the events. Grab samples were also taken two times a week and total of 104 samples were taken during the period from 06/11/2014 to 16/12/2015 under the random sampling approach or sampling approach 2 (SA2). On each sampling day, water flow was measured using an acoustic flow tracker. The water level was registered from water level stock for the calculation of runoff and curve once a day. The parameters and the methods analysed in the laboratory were similar to the second source. Additionally, heavy metal samples were also taken every week, and a total of 30 samples were determined for analysing the content of Cd, Cr, Cu, Pb, Ni, Fe, Zn.

Data from sources S1 and S3 were used in Papers I and III (see Figure 3.2), where source S3 had data up to 2012 when the study was conducted. The measurement was continued up to 2014 and Paper II used data of all grab samples from 1995 to 2014 for the outlets of 7 watersheds in Tallinn. Dissolved oxygen, conductivity, temperature and microbiological parameters had data for either less than 10 years or inconsistent. Therefore, these parameters were excluded from the data analysis. Since 2012, records have been available for discharge and sampling times, which assist in separating data into baseflow and stormflow. Paper IV used the data from source S4 where it has data of storm events, 104 grab samples from 2014 to 2015 and 30 heavy metal data for Mustoja basin. Other input data sources are described in the "Model development" section in this thesis and in Paper IV.

To date, the rainfall data from Tallinn-Harku meteorological station, which is approximately 6-20 km from the study area, was used for stormwater runoff estimation. For this study, the hourly consistent rainfall data from the same station was obtained from the Estonian Meteorological and Hydrological Institute (EMHI) for 10 years from 2005 to 2014. Paper I, II and III used these rainfall data. Rainfall depends on the time, space and altitude in the catchment and it suggests the measuring equipment should be in close proximity so that the consideration of climatic factors, characterisation and modeling of stormwater drainage system can be taken in a reliable way. Since 2013, rainfall data from other 9 stations installed by As Tallinna Vesi has been available. TUT also installed a tipping bucket rain gauge named "Saarma" station in May 2014 within the Mustoja basin on the downstream area near Saarma street. After applying the Thiessen polygons method in ArcGIS, the "Tondi 90" and "Saarma" stations were found to be influential for the Mustoja basin. One-minute rainfall data from these two stations were integrated for simulation in Paper IV.

The average monthly temperature (in Harku station) and rainfalls recorded in three stations (Tondi 90, Saarma and Harku) during Jan 2014 to Feb 2016 are presented in Figure 3.3. August 2014 and July 2015 were the wettest months while February to April were dry months in 2014 and 2015. Besides these, October 2015 was the driest month. Compared with the normal rainfall pattern

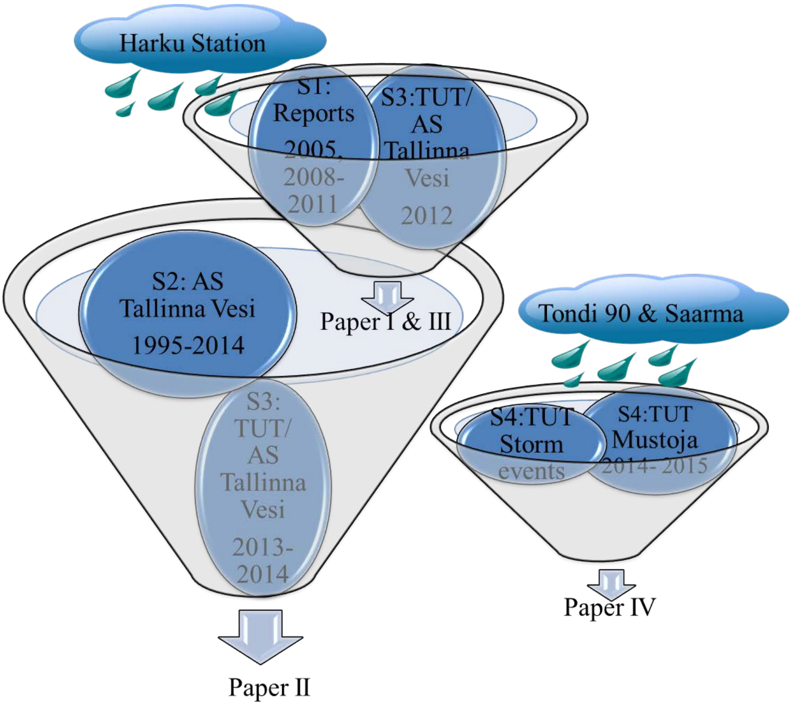


Figure 3.2 *Data sources for Papers I–IV*

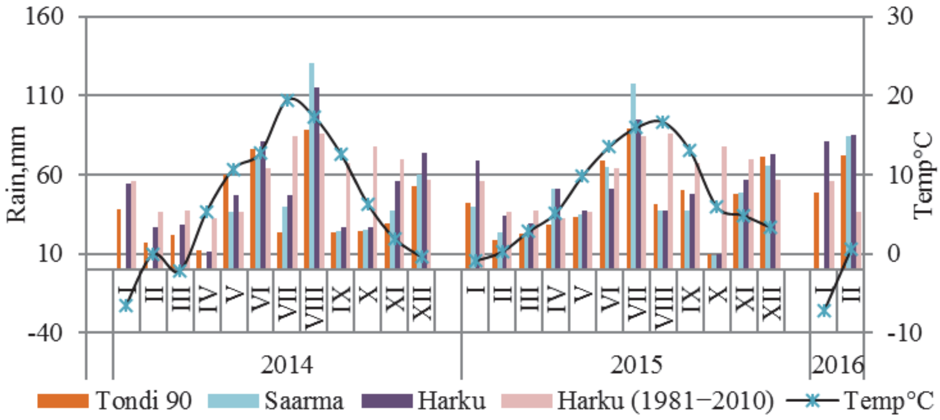


Figure 3.3 *Monthly temperature, monthly rainfalls in three rain gauge stations and long-term average rain.*

of Harku station (1981–2010) (EWS, 2015), these two years were dry years with approx. 34 % and 26 % less rain in 2014 and 2015 respectively. There were slight differences in the rainfall records in these three stations. In 2014, total rainfall in Harku station was 568.4 mm, but in Tondi 90 it was 466 mm, with a difference of 102.4 mm (Table 3.2). Rainfall charateristics such as rainfall intensity, peak rainfall, total rain and duration measured in Harku station was slightly higher than Tondi 90. In 2015, total rain in Saarma station was higher than Tondi 90 and Harku station was higher than Saarma Station.

Most of the rainfall characteristics in Saarma station were also slighly higher than the Tondi 90 station. These differences indicate rainfalls have local origins and stations near the reference catchment can minimise the error of spatial variation.

Table 3.2 *Rainfall events comparison among Tondi 90, Saarma and Harku stations*

Station (Months)	**Year**	**No. of events**	**total rain (mm)**	**Mean Rainfall Intensity (mm/hr)**	**Peak (mm/hr)**	**Total Event Rain (mm)**	**Duration (hrs)**	**Inter-Event Time (hrs)**
				mean	**mean**	**mean**	**mean**	**mean**
Tondi 90 (I - XII)	2014	150	466	0.6	1.2	1.6	6.8	58.2
Harku (I-XII)	2014	154	568.4	0.7	1.5	1.8	7	56.7
Tondi 90 (V-XII)	2014	107	363.4	0.4	1.3	1.7	7	52.8
Saarma (V-XII)	2014	98	423.2	0.5	1.9	2.2	6.5	57.7
Tondi 90 (I-XII)	2015	156	522.7	0.3	1.1	1.7	8.1	55.2
Saarma (I-XII)	2015	144	549.6	0.4	1.3	1.9	7.7	59.8
Harku (I-XII)	2015	NA	591	NA	NA	NA	NA	NA

3.3. Data processing, reviews and analysis

In this section, the methodology applied for gaining the objectives of the study as in Figure 3.4 will be discussed, which includes methodologies for assessing stormwater status in Tallinn, determining trends, assessing suitable sampling approaches and model development.

3.3.1. Assessment of stormwater status in Tallinn

The first aim was to assess the status of stormwater in Tallinn. At the beginning of this PhD study, the Estonian government had not initiated stormwater strategy; this remained the case until June 2012 when it first adopted the regulation “Tallinn Stormwater Strategy until 2030”. It was necessary to overlook the position of stormwater runoff, pollution load, variability and the data representativeness to estimate true loads because the type of mean measurement was not explicit. Data were available up to 2012 when Paper I was prepared, the monitoring programme was continued and the complete data up to 2014 were used in Paper II. Therefore, the updated analysis was performed where the descriptive statistics was applied to summarise the data for mean, median, range, 10th and 90th percentile. Correlation coefficient was estimated to look at the relationship between parameters. Seasonal indices were calculated to analyse the seasonal variation. The method of simple average was used to measure seasonal index, which measures how a particular season compares to the average season. When it is above or below 1, it indicates seasonality. Monthly seasonal indices were compared with relative average rainfall depth.

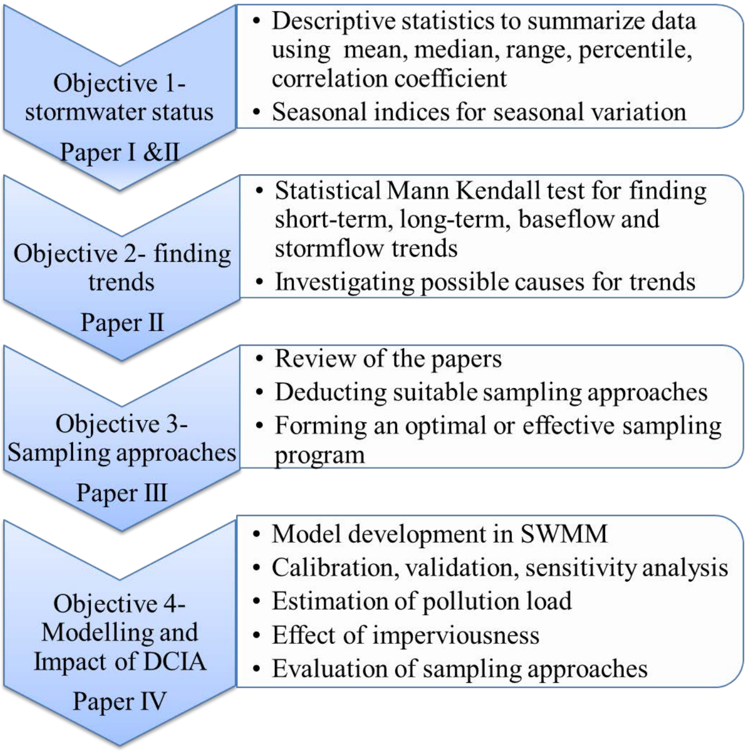


Figure 3.4 *Methodology applied in the study*

3.3.2. Determination of trends

The second objective was important in terms of understanding the temporal change in stormwater concentrations over the years. Monotonic trends in time series on the watershed basis were analysed using the Seasonal Mann Kendall (SMK) test (Hirsch & Slack, 1984), the details of which are explained in Paper II. Water quality data are usually not normally distributed and exhibit a seasonal pattern (Gilliom & Helsel, 1986). SMK tests are non-parametric tests for the detection of trends in time series. It provides a way for the accounting of ties and missing values. The test estimates the test statistics called SMK statistics (SMK-stat). The dataset was first separated into seasons and MK statistics was estimated for each seasons to bring together all signs of differences in the dataset. MK statistics were summed over all seasons to get SMK statistics. The test statistic has approximately standard normal distribution according to the central limit theorem. In this test, variance was corrected for ties and serial correlation among seasons during this test (Hirsch & Slack, 1984).

The data was splitted into two sets for baseflow and stormflow. Baseflow includes the data taken after a period of at least 3 days without rain (Schiff, 1997; Francey et al, 2010) or rainfall <2 mm/hr (a minimum threshold)(Butler & Davies, 2004); otherwise, the data belongs to stormflow. Two sets of data were formed such that the long-term (18-19 years) data from 1995 to 2014), short-term (10-year data from 2005 to 2014), baseflow and stormflow (same 10-year data) trends could be analysed. SMK statistics and significance levels were estimated, trend analysis was made, differences between trends were evaluated and the possible causes were investigated. After performing a two-tailed test, significance ranks were provided as 3 for $p \leq 0.05$ indicating statistically significant, 2 for $p > 0.05$ and < 0.20 indicating trends could exist if $p < 0.20$ and no trend for $p > 0.20$. The positive and negative sign determines an upward and downward trend. There are three factors that drove the performance of the short-term trend test. First, some sites did not have 19 years of data but only 10 years, as in the Ülemiste polder. Second, consistent hourly rainfall data was only available for this period in order to categorise stormflow and baseflow. And third, the trends observed in the long term could disappear in the short term or vice versa.

3.3.3. Approach to effective sampling programme

After understanding the status and trends of stormwater over the years, it was found that the variability and consequent uncertainty are high in data measurement, and even higher within a single year. The question arised as to how the representative data to all storm events can be acquired. The sampling programme has a high contribution in uncertainty development. Therefore, the third objective was obliged, in which the study was based on the literature reviews of relevant published papers, robust monitoring programmes, protocols and guidelines (Paper III). The important aspects of the monitoring programme are the selection of monitoring locations, sampling parameters selection, discharge measurement and the sample collection system that includes sampling mode, frequency and storm numbers. Different methods, criteria and uncertainties from previous analyses related to these aspects were studied. Effective and recommended methods were assessed so that the selection of methods for monitoring could be made according to the required criteria and certainty. The results were reduced to suitable sampling approaches and ultimately to propose an optimal sampling programme that was recommended for Tallinn city. In most cases, the cost of sampling methods is proportional to the increase in certainty but the constraint in the budget often intervenes to apply a more advanced method. Therefore, information about the options of methods with relative uncertainties will be helpful in picking the one that balances budget and quality output. While forming an optimal and effective monitoring programme, the local criteria and budget constraints were also considered.

3.3.4. Model development

The final objective was to use the model as an alternative approach acquiring stormwater quality and quantity when it is not possible to perform the comprehensive sampling programme. In addition, it is to evaluate the cost effective sampling approaches that can produce representative data to compare the results from modeling and time based sampling programme for events. The emphasis is also given in imperviousness because the mixture of different land uses in a large catchment basin has a significant effect on stormwater quality (Lee et al, 2009).

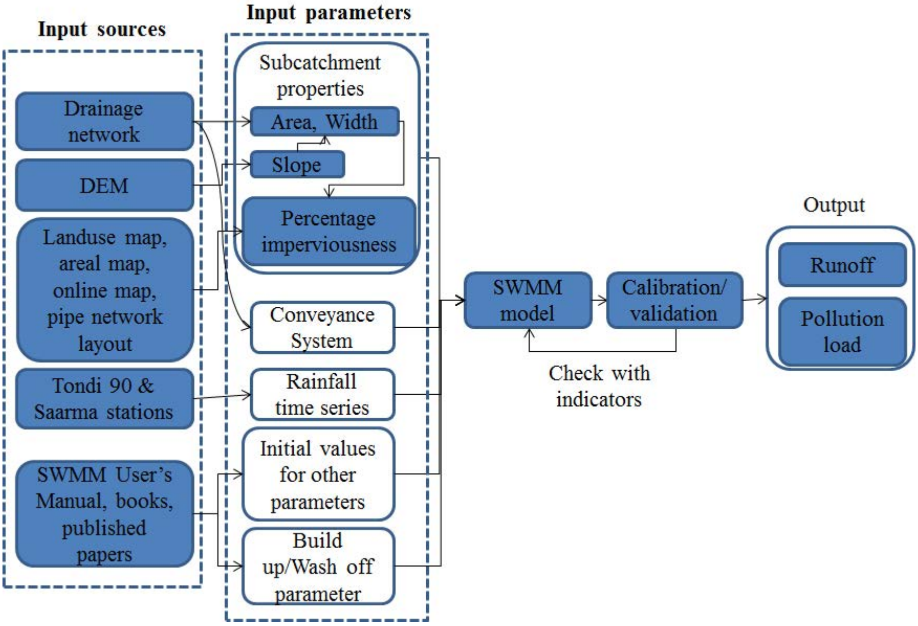


Figure 3.5 *Model development*

The model was developed in SWMM using the methodology described in Figure 3.5, the summarised picture of model development from Paper IV. ArcGIS was applied for preparing the conveyance system and the input sub-catchment properties e.g., sub-catchment area, width, surface slope, impervious percentage, etc. Other input parameters of sub-catchment properties, such as pervious and impervious depression storage (D_{per} and D_{imp}), pervious and impervious surface roughness (N_{per} and N_{imp}), infiltration parameters, buildup and washoff components, were set by adopting values from SWMM user's manual (Huber et al, 1988), books (Bedient & Huber, 1988; Wanielista, 1990) and published papers (Temprano et al, 2006; Nazahiyah et al, 2007; Chow et al, 2012). Rainfalls in time series from the Tondi 90 and Saarma stations, which are close to the basin, were spread over the sub-catchments.

Sub-catchments were delineated using the drainage networks and surface slope. AS Tallinna Vesi provided the details of drainage networks, which include location/elevation, manholes, pipe diameter, pipe material and year constructed. In the Mustoja catchment basin, separate drainage systems were mainly constructed over the course of 79 years. Approximately 51 km length and 0.15−2m diameter of drainage pipes with 4 km of drain ditches were found. The surface slope was determined using a 1m resolution digital elevation model (DEM) provided by the Estonian Land Board. The total number of sub-catchments is 378 ranging in size 0.06−23.8 ha, slope 0−11.1 % and width 25.8−3002.8m.

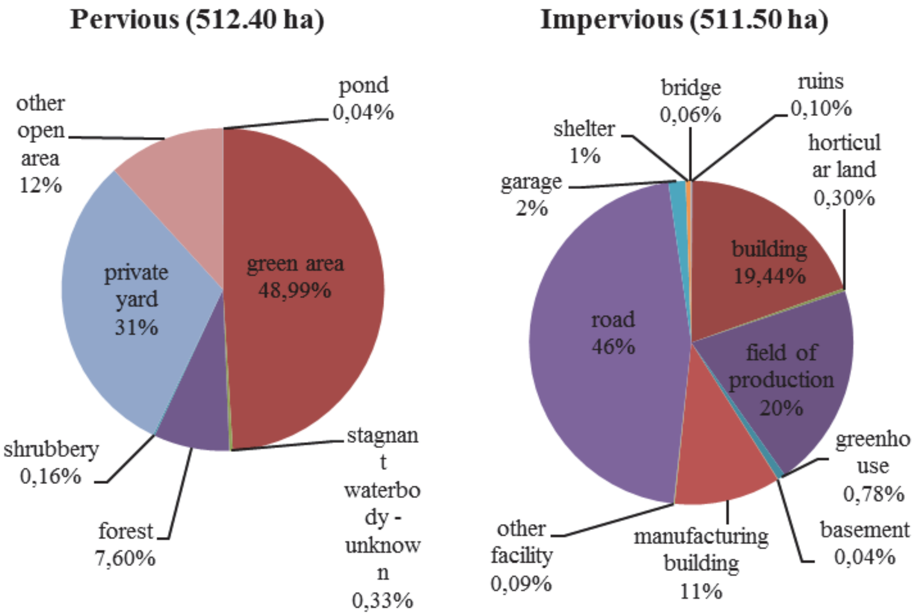


***Figure 3.6** Land use details within the catchment*

Identifying a directly connected impervious area and its impact on the total runoff and pollution load was sought to find the specific DCIAs, which require more attention in order to implement the control measures effectively. At the first stage when the land use map obtained from the Estonian Land Board for the year 2014 was investigated, approx 50 % of land in the Mustoja basin was found to be impervious, covered mostly by roads, fields of production sites and buildings (Figure 3.6), whereas pervious surfaces mainly consist of green areas and forest/private yards, forming ¼ and 1/5 of the total catchment area. Total impervious area (TIA) (in Table 3.3) was estimated using runoff coefficients acquired from Estonian standard EVS 848:2013. However, this TIA does not contribute to the actual runoff because the portion of it that is hydraulically connected to the storm sewer system is an important parameter (Lee & Heaney, 2003; Ebrahimian et al, 2016). Therefore, DCIA was identified and separated from directly not connected impervious areas (DNCIAs) in accordance with the procedure explained in the paper by Lee and Heaney (2003). In ArcGIS, the imperviousness was anlaysed after determining DCIA using field investigation, aerial maps, online maps and stormwater network layout. A simplified land use was prepared as in Table 3.3 by grouping various land uses into residential, commercial, industrial, forest, waterbodies, roads and roofs. Approximately, 55.7 %, 7 %, 10.2 %, 23 %, 3.9 % and 0.2 % of areas were determined as residential (R), industrial (I), roads (Rd), residential roofs (Rr), commercial roofs (Cr), forest and water, respectively. In the DCIA part of the table, DCIA was found to be nearly 27 % (278 ha) of which TIA was 79 % (217 ha) and effective impervious area (EIA) of 57 % (156 ha). EIA was estimated because again all the runoff does not enter the inlets despite the fact that the DCIA only represents the land use connected with the drainage system. Nevertheless, when the DNCIA was included, TIA was 44 % (448.9 ha) and EIA was 19 % (198.4 ha). DCIA roads are the major EIA, then DCIA commercial roof, followed by industrial areas and residential areas.

***Table 3.3** Simplified land use classified into DCIA and DNCIA of TIA and EIA*

Simplified Land use (LU)	**Area (ha)**	**Total %LU**	**TIA (ha)**	**EIA (ha)**	**Land use details**
DCIA					
Commercial Roof	55.9	5.5	50.3	33.8	commercial building, manufacturing building
Industrial	32.9	3.2	14.0	17.6	field of production
Residential Roof	38.6	3.8	34.7	10.4	building under construction, commercial building, private building, shelter
Road	147.5	14.4	118.0	94.2	bridge, roads (road as drain, DCIA road, feeder road, one side vegetated street)
Total	*274.8*	*26.8*	*217.0*	*156.0*	
DNCIA					
Commercial Roof	13.6	1.3	12.2	1.4	DNCIA manufacturing building
Industrial	71.3	7.0	26.4	3.6	field of production
Mixed Residential & Commercial	4.5	0.4	2.1	1.4	residential and commercial building
Residential	481.8	47.1	75.3	24.7	basement, cellar, garage, green area, horticulture land, other open area, private yard, Private yard, ruins
Residential Roof	48.1	4.7	43.3	4.8	DNCIA building, manufacturing building
Road	88.1	8.6	70.5	6.1	side vegetated street , road (road along with swale, road along with swale channel)
Forest	39.8	3.9	2.0	0.4	forest, shrubbery
Water	1.9	0.2	0.0	0.0	pond, stagnant waterbody - unknown
Total	*749.2*	*73.2*	*231.9*	*42.4*	

***Table 3.4** Sampled storm events*

Events	Antecedent dry days	Duration (hrs)	Mean Rainfall Intensity (mm/hr)	Peak (mm/hr)	Total Event Rainfall (mm)	Identity
Events for Calibration						
9/9/2014	12.1	2.3	2.2	8.7	5.1	Event 1
22/9/2014-23/9/2014	12.6	26	0.8	3.3	6.2	Event 2
4/12/2015-5/12/2015	1.5	13.5	1.2	3.1	9.7	Event 3
Events for Validation						
8/6/2014	0.9	9	2.12	6.5	3.5	-
6/11/2014	1.5	8.7	1	3.1	18.7	-
21/05/2015	1.1	8.8	1.11	2.4	8.13	-
6/8/2015	3	6.2	1.4	4.3	1.9	-

The model was carried out and the error was checked using four indicators: correlation coefficient (CC), relative error (RE), normalised objective function (NOF) and Nash-sutcliffe coefficient (NSF). The details of these indicators were described in Paper IV. Three storm events were used for calibration and four events for validation. The details of the events are presented in Table 3.4. The input parameters were changed in the range specified in Table 3.5 and predictive capabilities were checked through those indicators until the best-fit input parameters were found. The sensitivity of the input parameters that measures the effect of change was also analysed by estimating sensitivity coefficient (Sc). The output results of runoff and pollution load after calibration and validation were used for further analysis. First, the impact of DCIA was assessed and second the sampling approaches were evaluated.

***Table 3.5** Range of calibration and calibrated values for input parameters while simulating runoff quantity*

Parameters	Range (Reference)	Calibrated Values
% Imp factor	±10 %	0.9
Width factor	±10 %	1
Impervious depression storage	0.3 to 2.3 (Huber et al, 1988)	0.7
Pervious depression storage	2.5 to 5.1 (Huber et al, 1988)	3
Impervious surface roughness	0.01 to 0.03 (Wanielista et al, 1997)	0.0135
Pervious surface roughness	0.02 to 0.45 (Huber et al, 1988)	0.2
Maximum infiltration, mm/hr	50 to 200 (Bedient & Huber, 1988)	50
Minimum infiltration, mm/hr	0.5 to 12 (Nazahiyah et al, 2007)	0.5
Decay constant, L/hr	0.000389 to 0.0039 L/s i.e 1.4 to 14 L/hr (Nazahiyah et al, 2007)	4

4. RESULTS AND DISCUSSION

4.1. Stormwater quantity and quality

As stated in Chapter 1, the study reported here examined in details the status of stormwater quantity and quality in Tallinn city by addressing the first research question. It first reports the general statistics of stormwater in Tallinn by analysing 19 years of data from 1995 to 2015; it then examines the relationship between the sampled parameters; and finally it investigates the seasonality of those parameters. The results are based on Paper I and Paper II.

4.1.1. Overview of stormwater quantity and quality inTallinn

The spatial distribution of concentrations was illustrated based on descriptive statistics: percentiles, mean, median, minimum and maximum at seven outlets during the 1995−2014 period as in Figure 4.1. Over the 19-year period, the range of pH was more consistent as the mean and median were close to each other. The range of pH varies from 6.9 to 11.3 with mean ranging 7.4−9.0 and median ranging 7.4−8.9. Besides Härjapea, 90th percentiles of the observations were below pH of 8. In Härjapea, it was up to 10, exceeding the maximum allowable value. The stormwater in this outlet includes the possibility of discharges from Tallinn Old Town where the sewerage pipes were constructed during the medieval time and carbonate source as they are connected to old buildings, stonewalls, churches and stone pavements. The measurement of pH indicates acidity, basicity, alkalinity and neutrality in terms of hydrogen ions concentration in solution. The most preferable range of pH for the aquatic organisms is from 6.5 to 8, though the US EPA suggests 6.5 to 9 in freshwater as water quality criteria. The lower and higher ends of this range affect many species in terms of reproduction, growth and diseases. In Estonia, the pH of discharged water to the coastal area should be between 6 and 9 (RTI, 2013a). pH can occasionally exceed the limit in Härjapea, Lasnamäe and Rocca al Mare. However, the mean and median pH is smilar to neighboring countries as in the mixed urban in Vilnius city district where 224 samples showed the pH to be 4−8.7 (mean 7.3−8.1) (Karlavičienė et al, 2008). Similar results were obtained in Paris, France, where three studies in the residential area with private houses (261 ha), urban dense area with apartments (230 ha) and mixed urban land use (30 ha) showed a pH range of 6.99−7.87 (mean 7.43)(Zgheib et al, 2012).

Large variations were observed in SS, BOD and HC at ranges 1−774 mg/l, 0−303 mg/l and 0−17.1 mg/l respectively (Figure 4.1). On several occasions, TSS exceeded the national stormwater value of 40 mg/l and it accounts as 17.85 % of total samples. Also, the 90th percentile values ranged 42−110 mg/l excluding Lasnamäe and Ulemiste Polder, which indicates that SS has a higher possibility of exceeding the consent limit and degrade the water quality. Nevertheless, the mean and median of SS were 6−50.2 mg/l and 4−30 mg/l, but it did not exceed this limit aside from Rocca al Mare. Among the catchments, the catchment inducing discharge at Rocca al Mare was the most polluted in terms of suspended solids whereas the catchment's outfall to Ulemiste polder was the least polluted. The upstream of Rocca al Mare has water exchange activities e.g. wastewater discharges from the zoo, etc, which contribute to an increase in SS concentration. Ülemiste polder has a natural stormwater treatment system – wetland – that treats stormwater and decreases the harmful effects on the receiving waterbodies. Several studies in European countries found SS in large range e.g. 4−800 (mean 80−200) mg/l in Vilnius (Karlavičienė et al, 2008), 0.2−11560 (mean 68.2−133.6) mg/l in Espoo, southern Finland (Sillanpää, 2013), 1.8−736 (mean16.9−55.3) mg/l in the Polish city of Poznań (Baralkiewicz et al, 2014) and 11−874 (mean 106−413) mg/l in Paris (Zgheib et al, 2012). Even the event mean concentrations were larger than average concentrations as in Table 2.3. The average SSs in Tallinn were comparatively less than those studies. Nevertheless, the variation is high and the maximum amount of these parameters peaked up on several occasions. Higher peaks can be associated with heavy rainfall and snowmelt. Therefore, it is hard to conclude the clear effect of SS in most of the sites.

BOD concentrations within the period of 19 years were below the stormwater national limit value (15 mg/l) as in 6 out of 7 basins, 90th percentile BOD varies 1.7−14.0, excluding Rocca al Mare, which reached up to 19 mg/l (Figure 4.1). Yearly median shows that most of the observations taken before 1997 in the Mustoja and Rocca al Mare basins were higher than the limit. After that, only Rocca al Mare had several years with a higher than 90th percentile.

Nutrients causes potential impacts on the aquatic environment through eutrophication, and the Baltic Sea action plan has targeted reducing them from surface water flows in the coming decade. The stormwater limit in Estonia for TN is 45 mg/l and TP is 1 mg/l. These limits are excessively high than coastal water class 5 limit (0.97 mg/l of TN and 0.67 micromole/l of TP) and river's bad quality limit (6mg/l of TN and 0.1 mg/l of TP) (RTI, 2010). In 19 years of measurements, TN varied 0.8−145 mg/l and TP varied 0.1−8.8 mg/l, indicating a high variation in nutrient concentrations. During these observations, the 90th percentile of TN never exceeded limit value ranging 5.1–16.9 mg/l while 90th percentile TP were close to the limit value at two sites, as Pirita reached 1 mg/l and Härjapea 0.9 mg/l. The highest mean TN was at Russalka (8.3 mg/l) and the lowest was at Rocca al Mare (3.5 mg/l). Russalka, Lasnamäe and Ulemiste Polder had a higher mean TN than the others. However, the TP mean in Russalka and Ulemiste Polder were lower than other five sites. Indeed, Ulemiste Polder had the lowest of all at 0.1 mg/l.

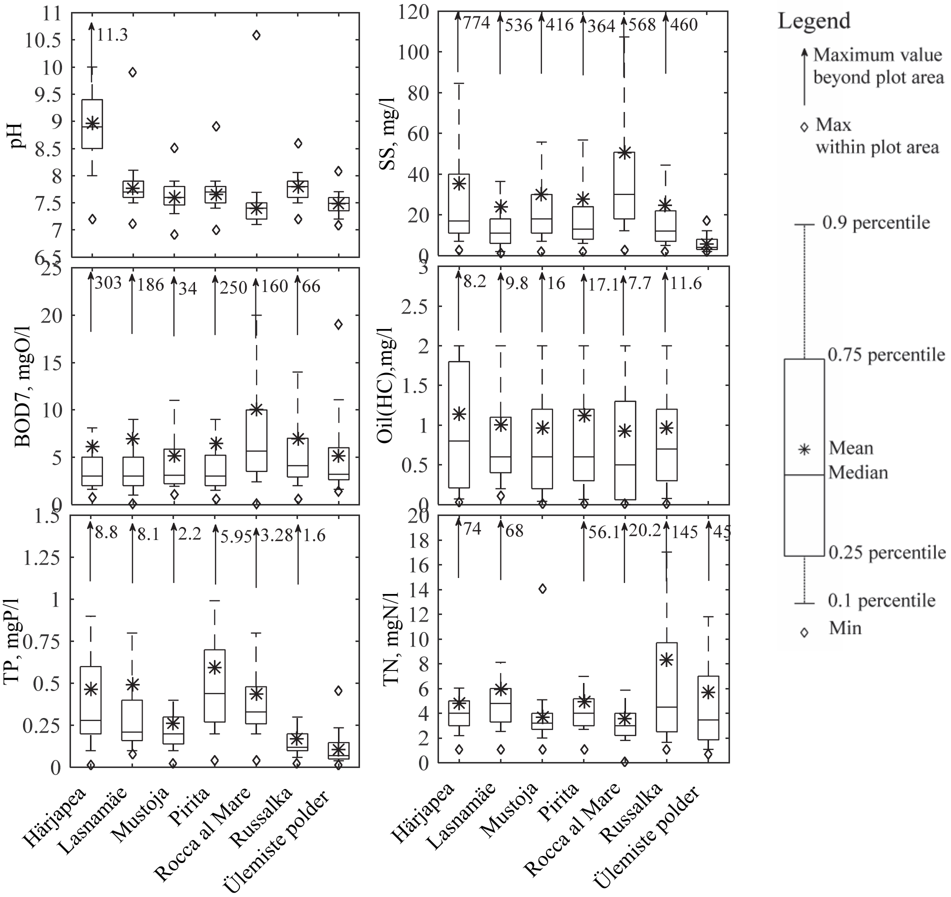


Figure 4.1 *Concentration range at different stormwater outlets during 1995−2014*

To illustrate findings of BOD and nutrients, based on recorded 90th percentile concentration and established limit values, BOD, TN and TP of stormwater has less impact on the water quality of the receiver. However, the studies conducted for the ecological status of coastal water in Tallinn Bay and Kopli Bay suggested that the coastal waters are in moderate to bad condition, and nutrient flux and oxygen depleting elements from stormwater have a considerable role in this (Erm et al, 2014; TCG, 2015). BOD occasionally exceeds the limit in Rocca al Mare and Russalka and the reason can be suspected from discharges of sewerages and old sewer line systems. It was found in the studies conducted in European countries, as in Table 2.3, that EMCs are higher in gully liquors and illegal connection to sewer systems (Lundy et al, 2012). Roofs and high density traffic roads are also contributors to a substantial amount of BODs (Göbel et al, 2007; Lundy et al, 2012). Nutrients from this study were higher campared to other European countries. For example in Espoo, Finland, TN ranged 0.2−24.6 (mean: 1.4−6.6) mg/l and TP 0.03−7.7 (mean: 0.11−0.22) mg/l (Sillanpää,

2013) whereas in Poland, TN was found to be 0.69−14.6 (mean: 2.7−5.7) and TP 0.02–0.57 (mean: 0.12−0.22) (Baralkiewicz et al, 2014). Sometimes, the concentrations during heavy rainfall with first flushes were found to reach the mean concentrations of inlet wastewater with yearly 90th percentile of 36.9 mg/l (TN) and 4.8 mg/l (TP). In many cases, a high TN can be expected from Russalka and Ulemiste polder whereas a high TP can be expected from Härjapea, Lasnamäe, Pirita and Rocca al Mare.

The Estonian stormwater limit value for HC is 5 mg/l and the measurements seldom surpass this limit (i.e. only 2.2 % exceeded) since 90th percentiles were below this limit varying from 2–2.6 mg/l based on catchment basins during the the 1995–2014 period (as in Figure 4.1). The range of HC was 0.3−17.1 mg/l, showing that occasional higher oil contents mostly occured during higher runoff. It was noticed that the annual 90th percentile between 2002 and 2004 exceeded the limit values in the Pirita and Rocca al Mare outlets. Oil products in stormwater runoff have been controlled effectively. Similar concentrations were observed in Vilnuis city (Karlavičienė et al, 2008), but they are higher than EMCs found in the studies of European countries (Lundy et al, 2012).

Dissolved oxygen (DO), conductivity and microbiological parameters were analysed in six sites because Härjapea did not have the data for these parameters. In Figure 4.2, the concentration range for DO and conductivity are presented. The mean concentration of DO in stormwater typically varies from 6.3 to 10.0 mg/l, with Ulemiste Polder at the lowest and Russalka the highest. Four other sites had better oxygenated runoff since they had consistent DO concentration with narrow range 8.8−9.6 mg/l. One study in the Polish city of Poznań found an even lower mean DO range from 4.9 to 7.2 mg/l (Baralkiewicz et al, 2014). In Ulemiste and Russalka sites, there were occasional high and low DO concentrations. In Ulemiste polder, 50 % data were below 5.1 mg/l of DO and 1st quartile data had DO concentration below 1.7 mg/l, indicating a deficit in oxygen content, which could influence fish life. However, the impact on the oxygen balance is important if secondary pollutants such as oxygen demanding sediments exist. Electric conductivity (EC) has high variation ranged 39.5 to 7900 µS/cm with mean 623.7−1368.5 µS/cm. Göbel et al. (Göbel et al, 2007)in their paper mentioned that EC are low from roofs at 25−269 µS/cm but high from densely traffic area at 108−2436 µS/cm. The high conductivity can be associated strongly with application of salts e.g. from deicing material. The data in Mustoja basin showed there is strong correlation of 0.97 between EC and chloride ions during the period from Nov 2014 till Dec 2016.

Coastal water, if mainly used for bathing purposes, should not be contaminated with bacteria and microbes. There are three public beaches on the Tallinn coastline that are not far from the stormwater outlets. The indicators used to investigate for faecal or bacterogical contamination were Escherichia coli (E.

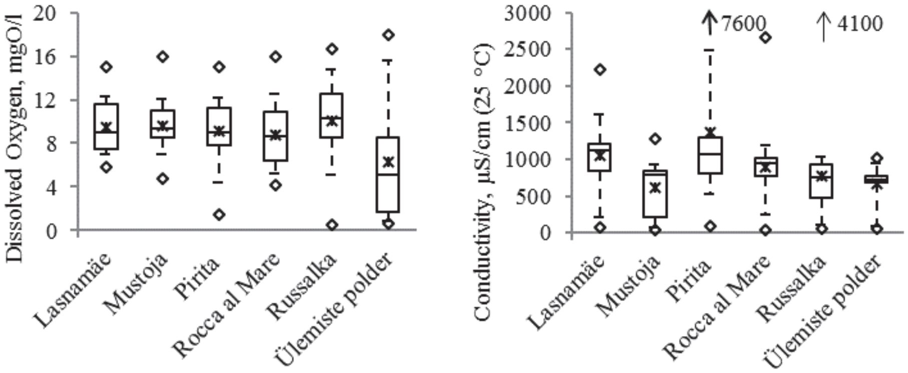


Figure 4.2 *Dissolved oxygen concentration and conductivity ranges at different stormwater outlets during 1995−2014*

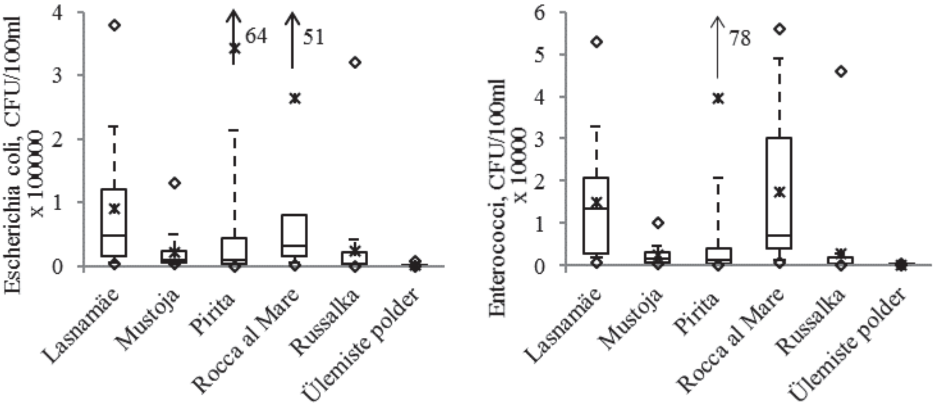


Figure 4.3 *Microbe ranges at different stormwater outlets during 2010−2014*

coli), Enterococci and salmonella. The European Union, as well as Estonia, has restricted microbiological parameters up to 1000 cfu/100ml E. coli and 400 cfu/100ml Enterococci for good bathing water quality (EU, 2006; RTI, 2008). The observations during the period 2010 to 2014 (in Figure 4.3) showed that microbilogical parameters in stormwater were often high ranging median values 2750−47500 cfu/100ml E. coli and 485−13500 cfu/100ml in 5 out of 6 sites, but Ulemiste polder had the lowest median E. coli (195 cfu/100ml) and enterococci (29 195 cfu/100ml). The variation was very large as E. coli ranged 0−64E5 cfu/100ml and Enterococi ranged 0−7.8E5 cfu/100ml, with extremes several times higher than the bathing water limit values occurring in Lasnamäe, Pirita and Rocca al Mare outlet. Rocca al Mare consists of water from the pools of the zoo and it is possible that some sanitary waste in those basins mixes with runoff. The studies revealed that in the urban cities, especially in the estuaries, the study of E. coli dynamics is quite difficult. The variability of E. coli in coastal water is rather large depending on the season, temperature and precipitation (Panasiuk et al, 2015). Stormwater studies shows E. coli concentrations are often very high, more than 50 000 cfu/100ml (Daly et al, 2013). Comparing with this, the lower median values indicate the status is moderate as suggested by the Estonian environment information centre (Estonian Environment, 2013). The trophic level in the coastal sea is still quite high despite the fact that the pollution load of Tallinn WWTPs has decreased remarkably since 1990 and discharges via deep outlets that extend beyond the coast; therefore, stormwater is still affecting the coastal sea.

In summary, the average concentrations of pollutants are not extremely high, aside from microbiological parameters. Even the 90th percentiles of pH, HC, TN and TP are below national permit levels. However, 90th percentile of BOD and SS in Rocca al Mare can exceed limit. Compared to coastal microbiological parameters, stormwater has moderate contamination. High content of pollutants can be expected in some basins, e.g, pH in Härjapea; SS in Härjapea, Mustoja, Pirita and Rocca al Mare, BOD in Rocca al Mare and Russalka; TN in Russalka and Ulemiste; TP in Härjapea, Lasnamäe, Pirita and Rocca al Mare; and microbilogical parameters in Lasnamäe, Pirita and Rocca al Mare. DO content is less in Ülemiste Polder.

4.1.2. Relationship between parameters

Analysis results for correlation coefficients (*CC*) for different parameters are shown in *Figure 4.4*, *Figure 4.5* and *Figure 4.6*. The relationships between parameters and flowrate in individual sites are illustrated with CC in Figure 4.4, between parameters and suspended solids (TSS) in *Figure 4.5*, and between parameters themselves in *Figure 4.6*. Flow did not have conclusive one sided positive or negative impacts on parameters aside from conductivity, which had weak negative correlation (-0.01to -0.29). Four out of six sites had positive correlation with SS ranging from 0.13−0.66 with Mustoja being the most correlated, and TN ranging from 0.06−0.52 with Ulemiste Polder being the most correlated (Figure 4.4). Microbiological parameters had opposite but weak relationships at five out of six sites, E. coli at -0.01 to -0.26 and Enterococci at -0.02 to -0.24. At least three parameters such as SS, BOD and TN in Mustoja, Lasnamäe and Rocca al Mare were positively correlated with the stormwater runoff rate and all the parameters had inverse relationships with flowrate in Russalka. Nevetheless, the overall relationship with flow in Figure 4.6 also shows flow did not have a strong correlation with any parameters. The relationships were quite site specific. For example, as mentioned above, SS had CC ranged from 0.13 to 0.66 but overall as in Figure 4.6, it showed a weak positive relationship at 0.13. This is due to the combined influence of negative relationships in Russalka and Ulemiste Polder sites. Ulemiste Polder receives water after natural treatment and, during heavy rainfall, the overflows from this outlet are discharge to the drain to Russalka. This activity on the upstream is the possible cause for the negative relationship in these two outlets.

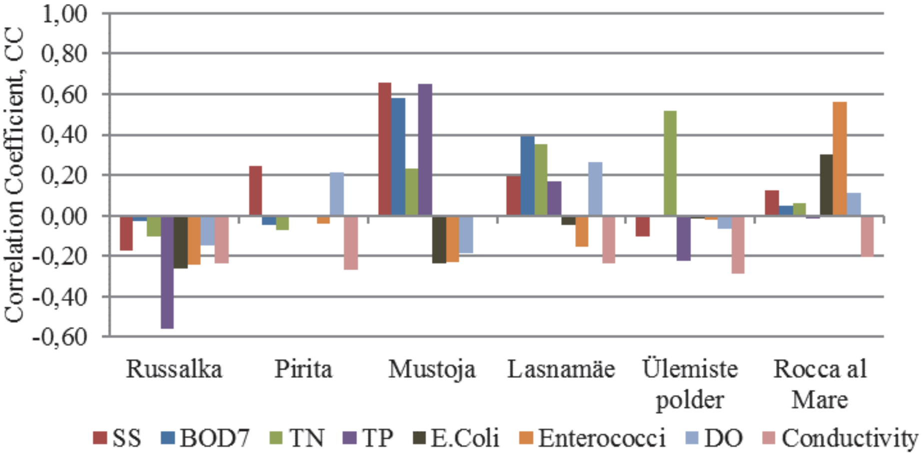


Figure 4.4 *Site specific correlation coefficient of parameters with respect to flowrate*

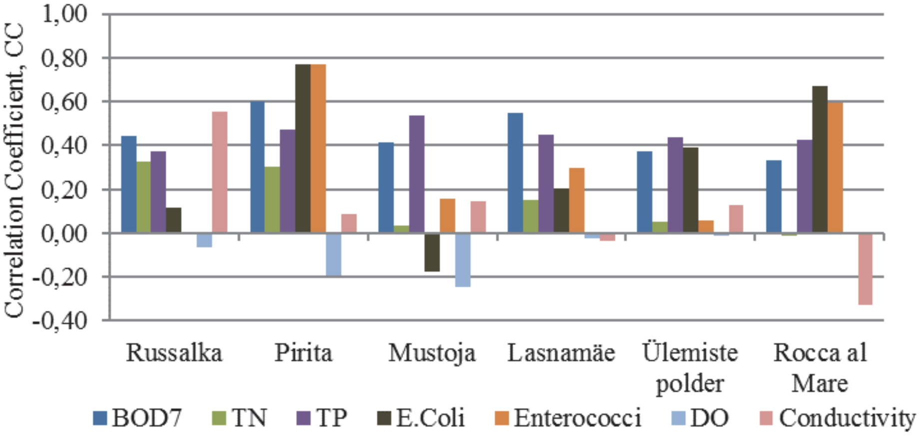


Figure 4.5 *Site specific correlation coefficient of parameters with respect to Suspended solids*

The results contradict when parameters are correlated with SS. Most of the parameters are positively correlated with SS (*Figure 4.5*). BOD, TN, TP and Enterococci had positive correlation in all sites whereas E. coli was negatively correlated in Mustoja alone. A higher and more consistent degree of relationships were found for BOD and TP at 0.33−0.60 and 0.19−0.54. Microbiological parameters were site specific as they had no relationship or a negative relationship in one site and high up to 0.77 in another site. Similar characteristics were also found for conductivity. DO had a weak negative relationship with SS in all sites. In *Figure 4.6*, the overall data verifies that SS can be moderately correlated with BOD, TP, microbiological parameters and HC, and weakly with TN, DO and conductivity. Similarly, BOD−TN and TN−TP had a moderate positive relationship at 0.41 and 0.39. A higher degree of relationship more than 0.6 was found for BOD−TP and microbioligical parameters with BOD, TP and TN. It was also revealed that oxygen content is associated with the presence of BOD, TN and TP; where their amount was higher in water, DO content was less.

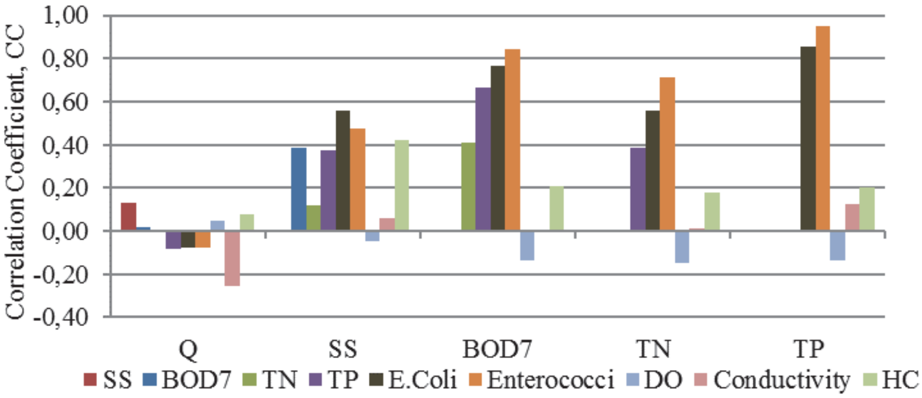


***Figure 4.6** Correlation coefficient between parameters*

To sum up, correlations between parameters are site specific. Flow has positive correlation with SS, BOD and TN in at least half of the studied basins in a range of 0.13−0.66 and 0.06−0.52, but the strong relationship is rare. While SS can be correlated moderately with BOD (CC: 0.33−0.60), TP (CC:0.19−0.54), microbiological parameters and HC, and weakly with TN, DO and conductivity. A higher degree of relationship more than 0.6 was found for BOD−TP and microbioligical parameters with BOD, TP and TN.

4.1.3. Seasonal variation

The method of simple average was used to measure indices for analysing seasonal variation. The seasonal index measures how the particular season compares with the aveage season. In other words, it compares the measured value to the one when there is no seasonal effect. When it is above or below 1, it indicates there is seasonality. Monthly seasonal indices are compared with relative average rainfall depth as in Figure 4.7 and Figure 4.8. Winter and spring had less than the average precipitation against the summer and autumn, and the snow period during winter and the start of spring had crucial runoff rates. In winter and spring, rain in Harku station was below the average in December until May (Figure 4.7), but the average runoff rates were nearly one and a half times more in the early two months of winter and early first month of spring, and that can be related to the consequences of snowmelt which resulted in increased runoff. During summer and autumn, however, the rain exceeds the average at 9 to 47 % in summer and 14 to 33 % in autumn for only three months i.e. early summer and the late months of autumn appeared to have higher than average, while other months have a deficit of runoff, indicating fewer runoffs were measured and the possible reason associated is the fewer number of storms that were recorded.

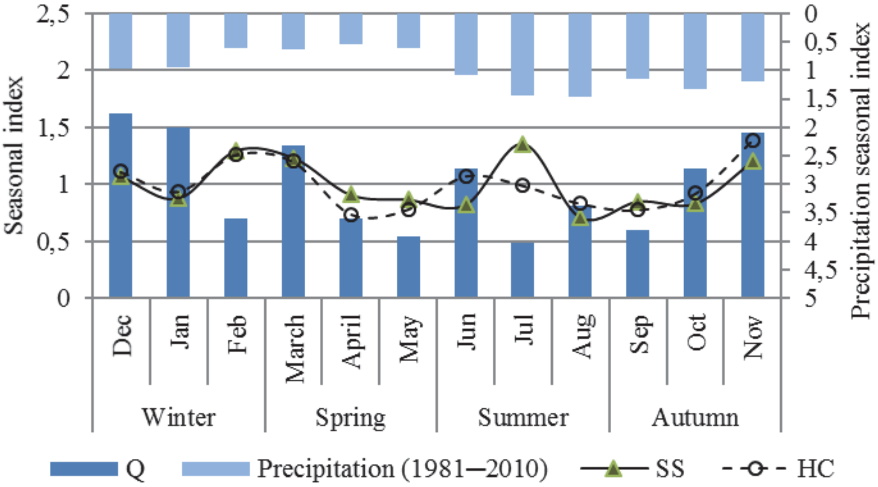


***Figure 4.7** Seasonal indices for flowrate, SS and HC*

SS and HC concentrations were higher during the end of winter and start of spring. During the seasons as a whole, February in winter, March in spring and November in autumn were crucial months for the higher than average discharge of both SS and HC, as they were found 20 %–29 % and 11 %–39 % more than average in the stormwater runoff. Among these months, February had low rainfall resulting in low runoffs, but SS was high and HC followed the seasonable variability. In Tallinn, there is usually snow cover for most days in winter. The dirt and emissions from vehicles gradually accumulate on the surfaces, which concentrates in the runoffs in the late months of winter. When the temperature mostly becomes positive at the end of February and in the first half of March, the snow starts to melt and the built up of pollutants are washed off producing high runoff and pollutants in the month of March, as in Figure 4.7 The temperature starts to rise from March and for a further two months, the dry period proceeds. Seasonal first flush mainly occurs in June and the heavy rainfall occurs during July and August. The runoff concentration during heavy rainfall depends on the antecedent dry days, catchment properties and the upstream human activities. The observations during July, August and September did not represent the rainfall patterns and the SS and HC were below average, except in July, which had a 35 % higher SS concentration than the average.

The effect of seasonal first flush were clearly observed for TP and BOD in two months (*Figure 4.8*): March, the start of spring and snowmelt where TP was 7 % and BOD was 69 %, and June the start of summer and rainfall after a long dry period where TP was 12 % and BOD was 36 % above the average. They were low at the dry weather (spring: April) and snow period (winter: December). The

TN seasonal index starts to peak as the winter proceeds and declines from spring. All months in winter had TN seasonal indices greater than 1 with a peak 24 % higher than average, showing that winter is crucial for TN build up.

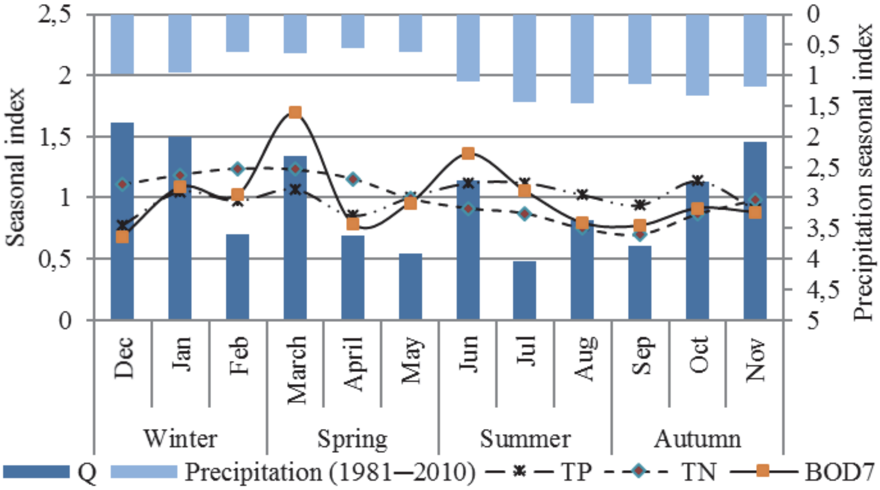


Figure 4.8 *Seasonal indices for TP, TN and BOD*

In summary, as for seasonal variation, higher concentrations of SS and HC along with a large volume of runoff are transported during the end of winter and start of spring, yet the actual runoff in summer and autumn is missing which masks the results during these two later seasons. Seasonal first flush for TP and BOD can be expected during the start of spring and start of summer while TN build up mainly occurs in winter time and wash off starts from spring. Similar results for seasonal variation of SS and runoff was suggested in Paper I, but the observations were few in the paper. Another difference from the previous paper is that the runoff is compared with rainfall in this study.

4.2. Trends in stormwater quality

This section is organised in terms of the second research question about finding the trends of stormwater quality to determine whether there is change in concentration amount over the years or not. An increase and decrease in the stormwater quality over the long term or short term provides information about how well the stormwater reduction activities have worked once implemented, the possible causes to the changes and the feedback on further strategies. This study aimed to find those trends in assessing the long-term (1995−2014) and short-term (2005−2010) period, as well as the influence of baseflow and stormflow on them. The results are based on Paper II.

4.2.1. Long-term and short-term trends

Statistical SMK test results from trend analysis were presented in Table 4.1. The majority of stormwater monitoring stations in Tallinn showed a decreasing trend for HC, SS, BOD and TN during the last 10 years. However, only HC, BOD and TN had significant trends in at least half of the basins, indicating that they are decreasing significantly. From the trend analysis results, significant trends were found for HC in 6 sites (at P-value (p) = 0.001 to 0.036), BOD in 3 sites (at p=0.021to 0.039), TN in 4 sites (at p=0.01 to ~0.05), SS in a site (p=0.037) and TP in two sites (p=0.02 to 0.022) out of 7 sites over the last 10 years. Less significant decreasing trends ($p > 0.05$ and < 0.2) were identified for SS, BOD, TN and TP where the trends of SS were three, but others were one.

Upward trends were observed for pH and TP. Statistically significant long-term upward trends of pH were revealed in 5 basins−Lasnamäe, Mustoja, Pirita, Rocca al Mare and Russalka −at $p \leq 0.001$(*Table 4.1*), but only Pirita had continued the trend in the last 10 years. Ülemiste Polder has pH data from 2005 and a SMK test for this period reveals a significant upward trend at p-value 0.008. Four other basins still have less significant short-term upward trends where the p-value ranged 0.067−0.139. The change in trends indicates improvements in pH reduction. Nevertheless, the pH values were within the limit range of 6−9 (*Figure 4.1*), aside from Härjapea, which had 90th percentile of 10, but there did not exist any trends. For TP of Härjapea, there is an increase seen in the past 10 years and baseflow (at p = 0.089) is mainly contributing to this result.

The illustration of the causes for decreasing and increasing trends were explained in detail in Paper II. Here, they are summarised in brief. The downward trends of HC in Tallinn city can first be associated with the practice of street cleaning initiated through the city development action plan (RTI, 2013b; Tallinna Vesi, 2014) and second with the installation of sand and oil filters on the major roads and car parks (RTI, 2013b). Several studies have indicated that highways, car parks, roads and vehicle washing areas are the potential land uses that contribute high amount of HCs (Stenstrom et al, 1984; Göbel et al, 2007).

According to Paper II, the reduction in SS in a few sites can be associated with the reduced particulate matter in the air (EKK, 2015), the connection of WW to sewerage pipes (Tallinna Vesi, 2014) and reduced salt de-icing practices. Though four sites showed decreasing trends after 2005, the conclusive significant trend was less and did not ensure a reduction in SS within the whole Tallinn area. It was more site specific. It can be reasoned back to the high variation in SS concentrations (*Figure 4.1*). Overall, SS in Tallinn, though decreasing in 4 sites after 2005, neither has conclusive significant trends nor a clear influence from stormflow and baseflow.

The improvement in sewer networks, street sweeping (Tallinna Vesi, 2014), the decline in the use of agricultural land (Iital et al, 2010; Statistics Estonia, 2015) and in turn fertilisers have favourably influenced the decrease in BOD and nutrients (Paper II). There are other diffuse sources of BOD and nutrients in stormwater runoff. Rainfall is more concentrated with them once it flows through the surfaces e.g. roofs where there are organic pollutants like leaves, animal or bird excreta, flowers and pollen (Göbel et al, 2007). Vegetation in drains and ditches enhances decay and the decomposition of organic compounds to increase nutrients.

Increased pH trends in most of the basins were associated with four factors in Paper II. The first was increased alkalinisation due to acidic precipitation as the analysis of rainfall data from Harku station showed that the pH of the rainfall has a significant decreasing trend in becoming more acidic. The consequent phenomenon was the weathering of carbonate aggregates (Barnes & Raymond, 2009; Kaushal et al, 2013) in carbonate lithology (Reintam et al, 1999) and buiding materials (Bityukova, 2006; Notton & Systra, 2010). Additionally, sewage discharges and alkaline dust from roads were also causes for pH increase. The similar reasons were mentioned for a pH increase in the Härjapea stormwater outlet. Records showed the annual pH level increased to a maximum of 9.78 in 2002, and began to decline from 2003. However, it was not steady as in 2007 there was a high pH of 9.58 and in 2013 it reached 8.87. The fall in pH was related to the city government's initiation to improve the environment of Tallinn core city area. Nevertheless, the further investigation to ensure the cause for the high pH requires attention.

Table 4.2 shows how the sites are effective in reducing concentrations over the past 10 years. As we can see, Mustoja, Pirita and Härjapea were significant in decreasing oil, biological oxygen demand and nutrients, though Härjapea had an increasing trend of phosphorus. Also, Lasnamäe, Rocca al Mare and Russalka were crucial sites in decreasing oil content. Ülemiste polder was less important in decreasing BOD and TN. In contrast, only Rocca al Mare was seen to be active in decreasing SS, though Mustoja, Pirita and Härjapea showed decreases in SS to some extent. All sites except Härjapea contributed to increased pH, while Pirita and Ülemiste polder had higher relevance. The analysis of trends provided more details in the change in concentration over time. It contradicts the conclusion provided by AS Tallinna Vesi and Tallinn City Department where they concluded that the pollutants in stormwater systems have decreased, thereby considerably improving the quality of stormwater over the last 15 years (Pauklin et al, 2005-2011). Some of the parameters e.g HC, BOD and TN, have showed clear decreasing trends in at least half of the studied basins, but TP and

Table 4.1 *SMK Test results (modified from Paper III)*

Storm outlets	HC, mg/l		SS, mg/l		pH		BOD$_7$, mgO$_2$/l		TN, mgN/l		TP, mgP/l	
	P-value	Sig. rank	*P*-value	Sig. rank	*P*-value	Sig. rank	*P*-value	Sig. rank	*P*-value	Sig. rank	*P*-value	Sig. rank
18–19 years data (1995–2014)												
Härjapea	0.076	-2	-	-	-	-	0.008	-3	0.076	-2	0.07	-2
Lasnamäe	0.022	-3	-	-	0.001	3	-	-	0.117	2	-	-
Mustoja	0.001	-3	0.122	-2	0.001	3	0.006	-3	0.005	-3	0.001	-3
Pirita	0.007	-3	0.012	-3	<0.001	3	0.001	-3	-	-	0	-3
Rocca al Mare	0.006	-3	-	-	0.001	3	0.001	-3	-	-	-	-
Ülemiste polder	-	-	-	-	-	-	-	-	-	-	-	-
Russalka	0.009	-3	0.16	2	<0.001	3	-	-	0.032	-3	0.009	-3
10 years data (2005–2014)												
Härjapea	0.036	-3	0.091	-2	-	-	0.028	-3	0.011	-3	0.051	2
Lasnamäe	0.013	-3	-	-	0.139	2	-	-	-	-	-	-
Mustoja	0.021	-3	0.154	-2	0.088	2	0.021	-3	0.052	-2	0.02	-3
Pirita	0.034	-3	0.12	-2	0.038	3	0.039	-3	0.021	-3	0.022	-3
Rocca al Mare	0.001	-3	0.037	-3	0.067	2	-	-	-	-	-	-
Ülemiste polder	-	-	-	-	0.008	3	0.116	-2	0.121	-2	-	-
Russalka	0.008	-3	-	-	0.13	2	-	-	0.001	-3	0.125	-2
Baseflow												
Härjapea	0.117	-2	0.045	-3	-	-	-	-	-	-	0.089	2
Lasnamäe	-	-	0.117	-2	-	-	-	-	-	-	-	-
Mustoja	-	-	-	-	-	-	-	-	-	-	-	-
Pirita	-	-	-	-	-	-	0.197	-2	-	-	-	-
Rocca al Mare	0.067	-2	0.162	-2	0.051	2	-	-	-	-	-	-
Ülemiste polder	-	-	-	-	-	-	-	-	-	-	-	-
Russalka	0.183	-2	-	-	-	-	-	-	0.064	-2	-	-
Stormflow												
Härjapea	0.117	-2	-	-	0.194	2	-	-	-	-	-	-
Lasnamäe	0.052	-2	-	-	0.092	2	-	-	0.026	-3	-	-
Mustoja	0.069	-2	-	-	-	-	0.166	-2	0.014	-3	0.038	-3
Pirita	-	-	0.096	-2	-	-	-	-	-	-	0.151	-2
Rocca al Mare	0.015	-3	0.161	-2	-	-	0.056	2	-	-	0.155	-2
Ülemiste polder	-	-	-	-	-	-	-	-	-	-	-	-
Russalka	0.19	-2	0.173	-2	0.042	3	0.114	-2	0.19	-2	-	-

SS were still in doubt, since they have either less significant trends or the number of sites having significant trends are less than half. Moreover, pH has been increasing in most of the basins. Therefore, it can be concluded that, in general, most of the studied parameters are in decreasing trends in most of the basins except pH, which has a clear increasing trend. Significant TP and SS trends are still unclear, and these parameters require more reduction activities. pH requires more attention to ensure potential causes.

Table 4.2 *Trends detail based on sites*

Sites	Decreasing		Increasing	
	Significant	Less significant	Significant	Less significant
Mustoja	HC,BOD, TN, TP	SS		pH
Härjapea	HC,BOD, TN,	SS		TP
Lasnamäe	HC			pH
Pirita	HC,BOD, TN, TP	SS	pH	
Rocca al Mare	HC,SS			pH
Russalka	HC			pH
Ülemiste polder		BOD, TN	pH	

Most of the basins' trends have been influenced by stormflow rather than baseflow. For instance, HC's short term decreasing trends of 6 sites were the effect of 5 decreasing trends during stormflows. Similarly, stormflow is more influential for pH increase (3 out of 7 sites) than baseflow (1 out of 7 sites). In most cases, the decreasing trend in nutrients was formed during stormflow. Therefore, stormflow has a greater influence on HC, SS, pH, BOD, TN and TP trends than baseflow.

4.2.2. Accuracy of Mean

Stormwater characteristics in most of the cases are elaborated with event mean concentrations, annual runoff and mass loads. In order to understand the average effect, mean concentration and mean flow are basic elements. The consistency of mean values provides accuracy in results, but it depends on the dispersion of data. First, the coefficient of variance (CV) was estimated to measure the variability of data for different parameters, as in Figure 4.9, such that the possibility of central tendency can be analysed. The parameter with CV <1 has data less dispersed than the parameter with CV >1. Second, the relative standard error (RSE) was estimated, as in Figure 4.10, to have a percentage that can quantify uncertainty. It is the standard error divided by mean. The parameter with lower relative standard error has higher certainty with precise measurement, since it has relatively less sampling variation around the mean. In fact, data organisations often set reliability standards that their data must reach before publication. For example, the U.S. National Center for Health Statistics typically does not report an estimated mean if its relative standard error exceeds 30 %.

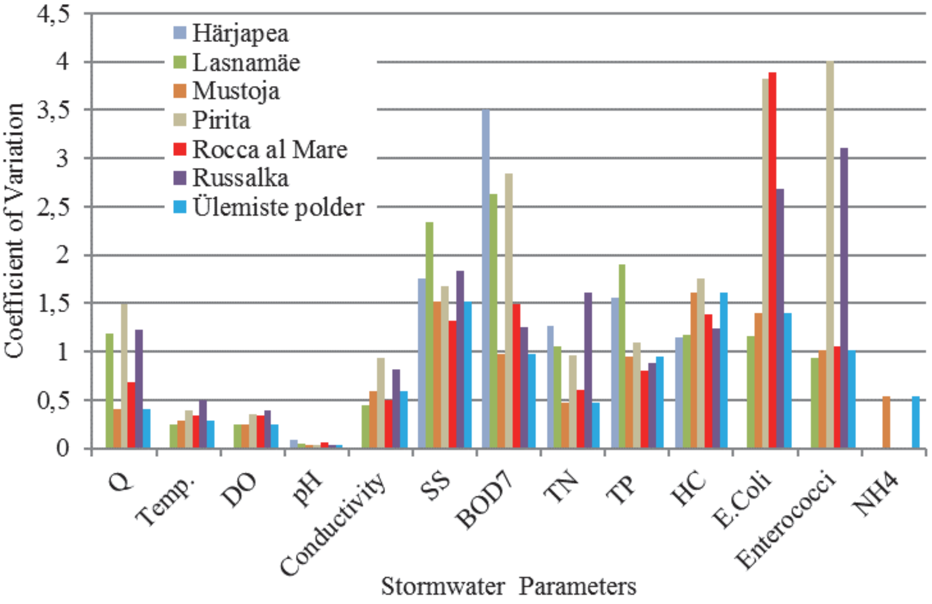


Figure 4.9 *Coefficient of variance of parameters*

In Figure 4.9, the CV of pH is near to zero, which indicates pH data have the highest consistency. Dissolved oxygen, temperature and conductivity have less variable data since CV is less than 1. CVs of flowrate, HC, TN and TP from some of the basins slightly exceed the value 1, suggesting the existence of variability, but not larger than that of the SS, BOD and microbiological parameters. The largest dispersion of data is found in microbiological parameters because the CVs in few basins are more than 3 while SS and BOD have CV around 2. When the data variability is linked with relative standard error, the influence of variability is seen in tandem. In addition, a large number of observations (n) assist in reducing the errors. Similar to CV results, RSE % for microbiological parameters are the highest at an average of >40 %; SS and BOD at an average of around 10 %; HC, TN and TP slightly <10 %; and other parameters below 10 %, except flow which is around 20 % (Figure 4.10). Flow data samples were fewer in number, as it has only 35 observations on average. When a few observations are taken, the error becomes expanded. For example, microbilogical parameters have few samples (n = 22), which increased their percentage of RSE. It implies that variability induces uncertainty and a lower number of observations increases error. In that sense, to produce high certainty, a large number of observations and/or less variability in measurements are required. It will be costly to collect and test the large number of samples and in most of the cases it is not feasible in the short term. It is challenging to obtain a few samples that have high certainty in results. Several studies have suggested representative data to the storm events can produce relatively high accuracy. In further chapters, we will dicuss the approaches in detail that can be used for acquiring coherent and representative data for stormwater quality and quantity.

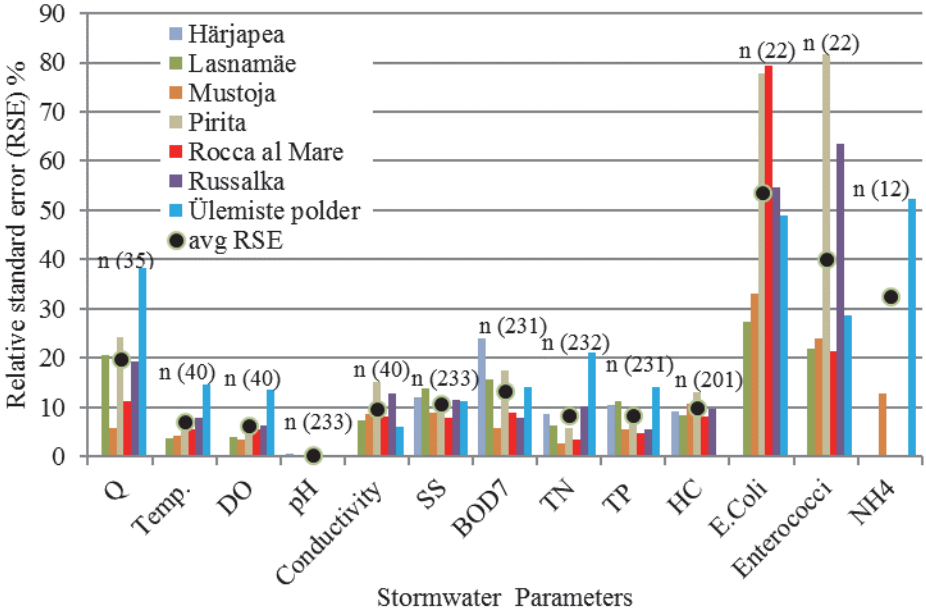


Figure 4.10 *Relative standard error of parameters*

4.3. Effective sampling programmes

A third research question arose when uncertainty is associated with the representativeness of data. Several researches revealed that uncertainty is higher in the data collection system, which is reflected due to error in sampling programme. This research question is covered in this section approaching the effective sampling programmes through literature reviews that are applied for setting an optimal sampling for Tallinn.

The results from the reviews are briefly summarised: first as suitable sampling approaches in Table 4.3, which includes the likely site selection approaches, monitoring parameters and sample collection systems, and second as the optimal sampling programme that was recommended for Tallinn city applying those information in Table 4.4. The details of these sampling approaches were described in Paper III. The important aspects from the suitable sampling approaches are:

- Site selection approach is important to optimise the number of sites because monitoring numerous sites is not only difficult to mobilise staff and equipment but also expensive in terms of cost. Moreover, it is applicable and cost effective to categorise sites into intensive and less intensive sites.

- While forming a minimum set of parameters to monitor, the approach of surrogate parameters can assist in choosing easy to measure parameters that minimise resource intensive laboratory experiments.
- Continuous measurement is indispensible, especially for mass load estimation and runoff volume. Stage discharge measurement is highly recommended because it has an associated stage-discharge relationship and provide reliable and accurate flow data with minimal maintenance. At limited location, velocity area method is excellent for determining an accurate discharge. Instantaneous flow measurement provides only snapshot flow at the time of measurement that can be used for developing database for stage-discharge rating.
- Automatic sampling is recommended for continuous measurement as it reduces human error, but grab sampling also has substantial certainty when properly sampled. Grab sampling is mostly preferred for certain parameters such as oil and grease. The parameters that do not have large variation throughout the storm can be monitored using grab sampling or baseline sampling. Automatic sampling gives an exact total pollution load but it is not very good when investigating natural processes requiring extreme concentrations.
- Flow interval/proportional sampling is superior to time interval/proportional sampling and grab sampling, as it has higher accuracy than others. However, whether to proceed with discrete, composite or grab sampling or a combination of them depends on the purpose of sampling (details in Paper III).
- In order to achieve a sufficient degree of certainty at a reasonable cost, the flow interval sampling frequency provided by King et al. (2005) and King and Harmel (2003) can be recommended for discrete sampling when the purpose is estimating peak flow/concentration, temporal variability and/or their combinations. The comparatively better sampling for estimation of EMC, SMC and mass load is flow interval composite sampling. If manual sampling has to be performed, 12 random samples could be the first priority (Leecaster et al, 2002) in comparison to other grab sampling frequency and timing because it could address the variability of contaminants in storm event and rainfall effects. The final alternative if the first priority is not affordable is to take a grab sample between 1–6 h of runoff or the middle of the storm.
- It would be a better option to sample at least 7 medium and large storms to attain higher certainty.

In Lithuania, sampling methods were changed from grab sampling irrespective of storm event in early research (Karlavičienė et al, 2008) to flow proportional composite sampling in recent research (Mancinelli et al, 2015). More up-to-date funded projects in Finland have used flow proportional composite sampling methods in order to attain a higher certainty of EMCs and pollutant loads (Sillanpää, 2013; Koivusalo et al, 2014; Valtanen et al, 2014). Nevertheless, it is

Table 4.3 *Summary of suitable sampling approaches*

Sampling programme components	**Suitable approaches**	**Related References**
Site Selection	• optimising the number of sites through pre-screening, screening, quick scan and final selection dividing into intensive and less intensive sites	1
Selecting potential Parameters	• using prepared contaminant profile	2
	• preparing minimum set of parameters e.g., physicochemical (pH, TSS), Nutrients, Heavy metals (Cd, Cr, Cu, Pb, Zn), PAH and PCB	
	• use of surrogate parameters -EC, turbidity, TSS, TDS, TOC and DOC	3
Discharge measurement	• stage discharge measurement	4
	• velocity area method	5
Sampling mode	• Automatic sampling for continuous measurement	6
	• grab sampling (especially for less variable parameters)	7
	• single intake sample	8
	• Flow interval/proportional sampling	9
	• selecting sampling method based on purposes using flowchart	10
Sampling frequency	• flow interval composite sampling for discrete sampling	11
	• single composite sample	12
	• 12 flow interval discrete sampling method	13
	• 12 random samples for grab sampling	13
	• grab sample between 1–6 h of runoff or the middle of the storm	14
Number of storms	• 7 medium and large storms per year	15
	• a maximum of 10 storms for temporal variability study	16

1= Langeveld et al, 2014; Lee et al, 2007; 2= Eriksson et al, 2005; Gasperi et al, 2012; Göbel et al, 2007; Ingvertsen et al, 2011; Kegley et al, 2014; Madrid & Zayas, 2007; Makepeace et al, 1995; Paschke, 2003; Zgheib et al, 2008; 3= Fletcher & Deletic, 2007; Miguntanna et al, 2010; Settle et al, 2007; 4= Slade, 2004; Harmel et al, 2006a; Buchanan & Somers, 1968; Sauer & Turnipseed, 2010 ; 5= McIntyre & Marshall, 2008; Nord et al, 2014; 6= Leecaster et al, 2002; Fletcher & Deletic, 2007; Lee et al, 2007; 7= Khan et al, 2006; Lee et al, 2007;8= Taylor et al, 2005; McCarthy et al, 2008; McCarthy et al, 2009; 9= Miller et al, 2000; Harmel et al, 2002; King & Harmel, 2003; Harmel & King, 2005; 10= Flow chart in Paper III; 11= King et al, 2005 and King & Harmel, 2003; 12= Harmel et al, 2006a, King & Harmel, 2003 and shih et al. (1994); 13= Leecaster et al, 2002; 14= Fletcher et al, 2007 ; Khan et al, 2006; Lee et al, 2007; 15 = Leecaster et al, 2002, May & Sivakumar, 2009, Maniquiz-Redillas et al, 2013;16= Mourad et al, 2005.

not always the case when available resources are limited and the number of sites is more rather than a few. The optimal programme has to be selected to meet these resources. The detail of this programme is illustrated in the section "an optimal and effective sampling programme".

4.3.1. Optimal sampling programme for Tallinn

The general monitoring programme (detail in Paper III) was deducted as in Table 4.4 using suitable sampling approaches for the usual conditions. In usual conditions, the purpose of sampling is to obtain the concentration to compare with the permissible limit and the usual issue in many countries is limited budget and resources. The site selection approach of optimising the number of sites and categorising into intensive and less intensive sites can be applied. For instance, in Tallinn, the available 66 monitoring sites, after screening using the method of site selection, can be reduced to 4 sites in one category requiring intensive sampling [sites A] and 4 sites in another category requiring less intensive sampling [sites B]. The procedures for selecting sites and parameters were illustrated in Paper III. The monitoring parameters can be categorised into primary and secondary parameters. In Estonia, some parameters are mandatory for monitoring according to the Estonian Water Act, Regulation No. 99. In addition, the primary parameters include those that have a potential risk and a great chance of occurrence in stormwater. Secondary parameters pose a potential risk to human or aquatic life if they are present in stormwater, but their presence often depends on upstream catchment characteristics and special activities. Comparatively, primary parameters need more intensive sampling than secondary parameters. Those recommended parameters may differ according to local conditions.

The sampling method depends on the purpose of sampling as already mentioned above. The sampling programme here described is for capturing peak concentration or the poorest concentration during storm events. Therefore, it is ideal to collect a large number of samples throughout the storm event. Since it is expensive to do such sampling in all outlets, it is practical and reasonable to perform intensive sampling for sites A and less intensive or grab sampling for sites B as shown in Table 4.4. This programme has another benefit in that the samples collected for peak concentration can be composited manually or automatically during intensive sampling in order to use them to calculate EMC, SMC and annual loads. Grab sampling is not recommended for intensive sampling unless there is a single site and short distance to the site because it is difficult to mobilise sampling staff and equipment to different sites at the same time. Nevertheless, it can be performed in sites B to find the peak concentration where a single sample is taken within 1 hour of storm commencement during first flush or seasonal first flush. Additionally, the installation of automatic water level measurement devices is recommended so that it can also measure some surrogate parameters continuously. In fact, the defined usual condition is also the practical situation in Tallinn city. Due to the similar conditions, this general sampling programme can be recommended for Tallinn watershed.

Table 4.4 *General monitoring programme*

Aspect	**Sites A requiring intensive sampling**	**Sites B not requiring intensive sampling**
Location	At point of discharge into receiving environment; and/or downstream of discharge in well-mixed area	At point of discharge into receiving environment; and/or downstream of discharge in well-mixed area
Flow measurement	Preference 1*or Preference 2* (required as a surrogate for flow hydrograph) or Preference 3*	Automatic stage measurement with surrogate parameters
Sampling method for stormflow		
Sampling mode	volume/flow-proportional automatic, but grab samples may be also feasible in some circumstances (e.g., short distance to sampling site, for oil and grease parameter etc)	Grab sampling
Minimum threshold	at least 3 days and/ or rainfall intensity 2mm/hr	at least 3 days and/ or rainfall intensity 5mm/hr
Sampling frequency	sample collection is more frequent during periods of higher or at initial runoff (0.5 mm) and greater interval for remainder (1.5 - 2.5 mm) as specified by McCarthy et al.(2008)	within first 1 hr for peak concentration during first flush and seasonal first flush; within 1-6 hr of storm event for EMC, SMC or annual loads as specified by Lee et al. (2007) and Khan et al (2006)
Number of samples	At least 12 discrete samples per event; at least 1 composite sample	at least 1 sample for peak flow; at least 1 sample for EMC, SMC or annual loads
Storm size	at least 7 storms medium and large	7 storms medium and large
Parameters	primary and secondary parameters	primary and secondary parameters

Preference 1*: stage-discharge measurement with the precalibrated structure installed preferably on the stable channel; Preference 2*: stage measurement using stillwell; Preference 3*: velocity area method using acoustic doppler flow meter

4.4. Model development for quality and quantity

The results from model development are based on Paper IV that aimed to achieve the final objective of this study. The alternative approach to attain stormwater dynamics that uses limited resources was already described as model development, and here its capability is analysed through model predictability and the findings of EMCs and total loads. Further, the model's beneficial implication about imperviousness, first flush and sampling approaches will be illustrated to provide the information for stormwater managment.

4.4.1. Model predictability

Results of model calibration for the prediction of stormwater quantity shows the modeled runoff is close to the observed runoff because three indicators are in the acceptable range. Correlation coefficient is 0.87−1 i.e. close to 1, NOF is 0.1−0.3 i.e. between 0 to 1 and NSC is 0.3−1 i.e. close to 1. However, RE is beyond ±10 % at flow error less than 20 % and peak error between -27.4 to +21.2 %. In contrast, quality prediction capability is moderate as NSC for TSS is poor but it is good for TP at 0.4−0.7 while RE for both quality parameters can go beyond the acceptable range; however, CC is yet in acceptable range as it stands at the range of 0.4−1. Similar results are found while verifying the storm events, RE % for volume is between ± 10 % in a range -9.6 to 6 % and peak flow is nearly ± 10 % in a range -11.0 % to 7.8 %, indicating the model can sufficiently predict stormwater runoff, but the quality prediction is not in acceptable range having RE % beyond ± 10 %. Overall, the model is acceptable for runoff quantity and it provides less accurate estimation for quality performance. Calibration through an increasing number of events can reduce the error to some extent.

After successful calibration and validation (details in Paper IV), calibrated values for quantity are presented in Table 3.5. The % imperviousness is obtained as 19.7 %, where the runoff coefficients for different land use varies as residential: 0.05 to 0.2, residential roofs: 0.15 to 0.20, mixed residential and commercial: 0.2 to 0.26, industrial: 0.09 to 0.45, commercial roofs: 0 to 0.56 and roads: 0.03 to 0.57, depending on the proximity to drainage system. The imperviousness is low, but other studies where the residential land use is dominant found rather lower impervious percentages e.g., 15.9 % in residential areas in Spain (Temprano et al, 2006) and 7.2 % in highly residential areas (Hood et al, 2007). A large area of pervious area and mixed land use probably resulted in such low imperviousness. Calibrated depression storage for impervious area is 0.7 mm, which is higher than the values of 0.15 and 0.29 as proposed for local context by Hood et al. (2007) and Koppel et al. (2014). In this study, this value is used as the average of dry and wet weather applied by Chow et al. (2012). Buildup and wash off parameters for quality calibration fit the values (Paper IV) that largely correspond to the findings of Chow et al. (2012). Build up is slightly higher in commercial areas than residential, and industrial has a slightly higher rate than commercial area. As a consequence, if the imperviousness of land use increases, washoff also increases. Wash off coefficients for DCIA roads and roofs are found to be higher than DNCIA, which indicates they are the potential land use for pollutant loads in runoff.

4.4.2. Pollutant loads

After simulation, EMCs for three events were estimated that were illustrated in Paper IV. TSS are 33.6, 50.3 and 69.1 mg/l; TP are 0.5, 0.5 and 0.7 mg/l; and mean runoff are 229.8, 187.6 and 422.6 l/s for event 1, 2 and 3 respectively. The total volumes of runoff are 16.3,16.0 and 20.0 million litres (ML) from 5.1, 6.2 and 9.7 mm rainfall events. EMCs of TSS in event 2 and event 3 exceed the national stormwater limiting value of 40 mg/l where as TPs are below the national stormwater limit value of 1 mg/l and in poor status of river quality levels being greater than class IV limit (i.e. 0.1 mg/l in annex 4, Regulation No. 99)(RTI, 2013a). The peak concentrations are higher, approximately 3 to7 times the national TSS limits and 1.4 to 2.7 times the national TP limits. When estimating event loads, stormflows in all three events are more polluted than baseflows at nearly 90 % of total load for TSS and TP (Figure 4.11). The stormflow volume has increasing tendency proportional to total rainfall whereas stormflow mass load seems to increase in proportion to rainfall intensity.

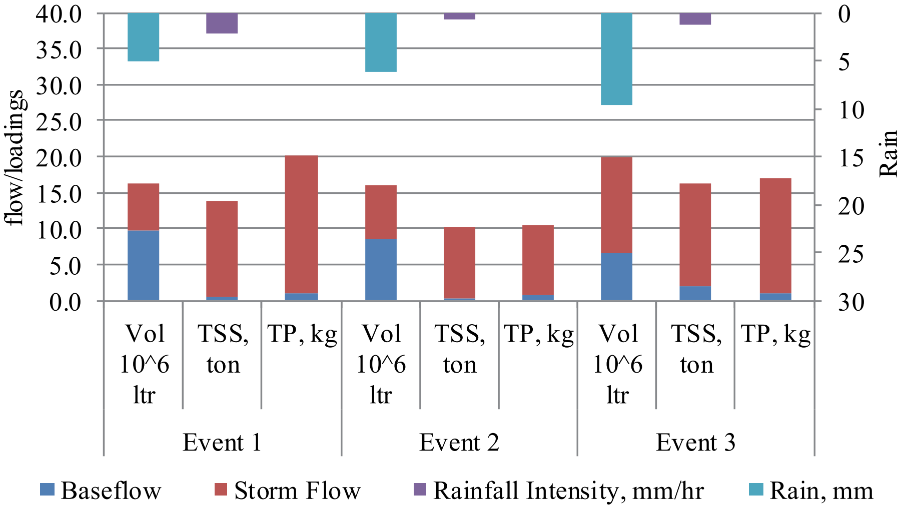


__Figure 4.11__ Event based baseflow and stormflow details

The annual outfall loadings are found to be 97.8 tons TSS, 1.5 tons TP from 4,400 million litres (ML) of runoff in 2014 and 110.7 tons TSS, 1.7 tons TP from 4,500 ML of runoff in 2015 (*Figure 4.12*). The simulated SWMM results were different from three other monitoring programmes. The first one was a monitoring programme during 2012−2014 conducted by Tallinn University of Technology, the department of environmental engineering (TUT DEE) and AS Tallinna Vesi at the outlet of the Mustoja basin approximately 500m downstream from the studied outlet. This programme was commissioned by Tallinn Environmental Board and the samples were taken 6 times per year. The same methodology was continued in the second monitoring programme but it was conducted by Estonian, Latvian & Lithuanian Environment (ELLE) group in 2015. The third monitoring programme was SA2, which was different in methodology in terms of sampling interval as the samples were taken twice a week. The differences in runoff and loads in these three sampling programmes are, indeed, not surprising because in ELLE measurement, there is high flow rate and extreme mean concentration, which develop high runoff and loads; in TTU DEE, there is low flowrate and low mean conconcentration, resulting in low runoff and loads; and in SA2, it is mainly due to the measurement of low concentrations. The consequent output runoff and loads produced a high error since the runoff calculation was based on daily average flow and load calculation based on mean flow and mean concentration.

However, the annual rainfalls in the SWMM system resulting from the combination of Tondi 90 and Saarma stations are less than rainfalls in Harku station by 25 % in 2014 and 11 % in 2015, the induced runoffs in other monitoring programmes are not proportional to rainfalls (*Figure 4.12*), pointing to errors in those programmes. Nevertheless, when comparing monthly patterns of rainfalls with their induced runoffs from SWMM, the results – particularly the runoffs – follow the trends of rainfall patterns as shown in Figure 4.13. Simulated runoffs and loads are the highest in August 2014 and July 2015, while lowest in September 2014 and October 2015 similar to the rainfall depth. January to April 2014 and January to March 2015 had effect of negative temperature and the simulation did not consider this effect due to less available data.

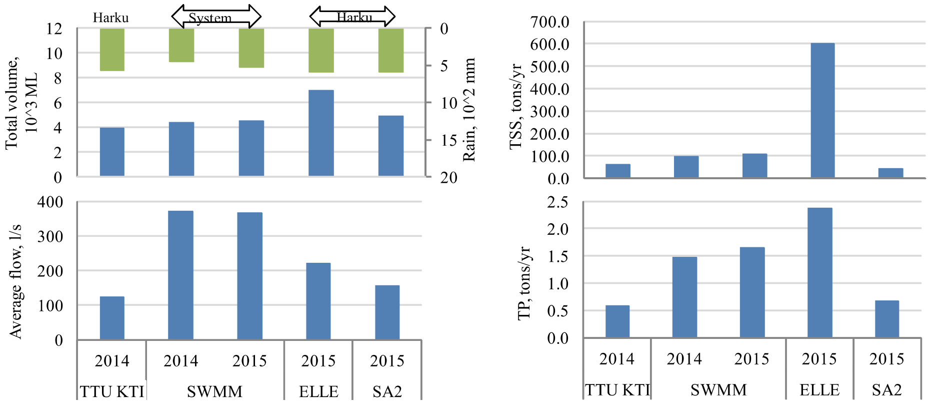


***Figure 4.12** Total annual runoff, average flow rate and total mass*

Acccording to Leecaster et al. (2002), volume weighted mass load estimation from the time weighted sampling has less error. As in Figure 4.14, SWMM results are close to the flowrate and annual load estimations from applied the time weighted sampling (SA1); however, there is a considerable difference in TSS and TP loads. These differences are probably due to the model's predicted uncertainty in quality estimation.

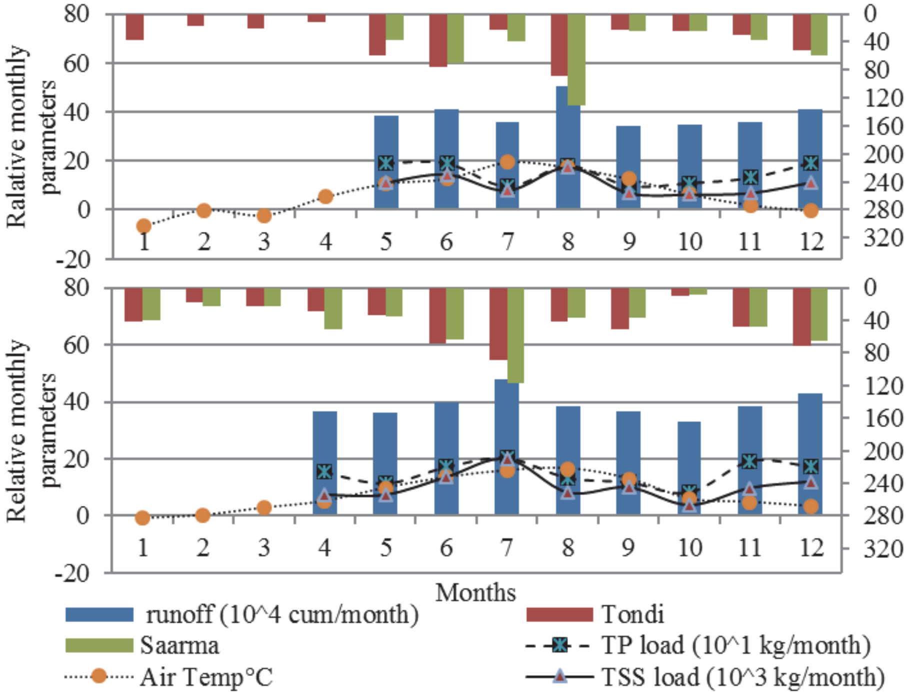


Figure 4.13 *Monthly temperature, rainfall, runoff, loads in year 2014(upper) and in year 2015(lower).*

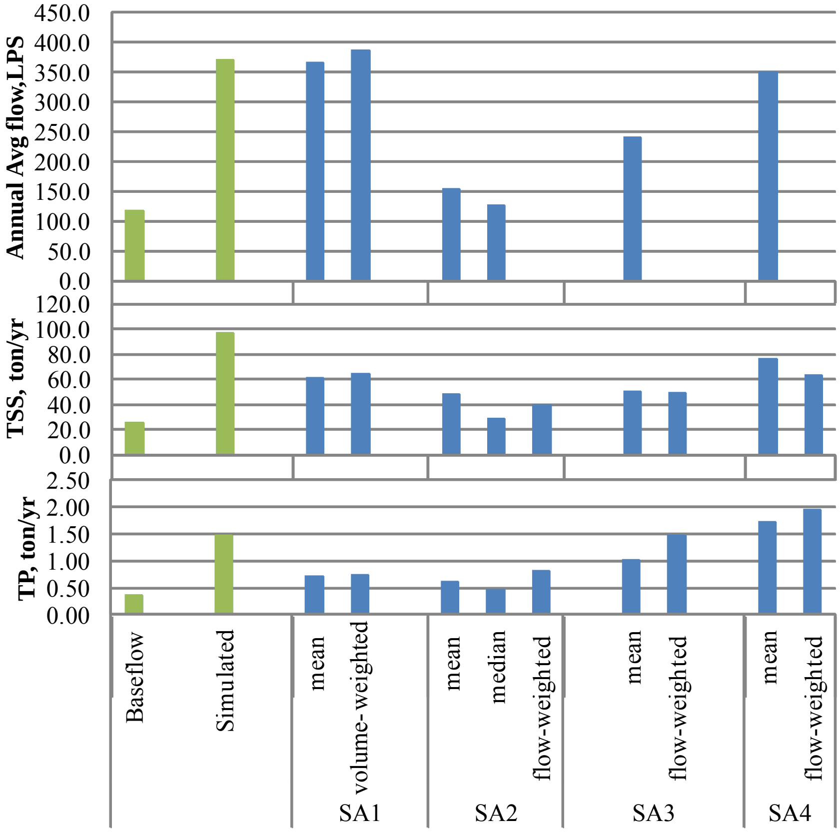
4.4.3. Model's implication

Evaluation of sampling approaches

The data representativeness in so far as they address the storm events and which sampling strategy at limited resources provide less error is always a question, and the answer is sought in this part. For this, outputs from SWMM, time weighted sampling (SA1) and three grab sampling approaches: random grab sampling (SA2), grab sampling within 6 hr irrespective of storm size (SA3) and grab sampling within 6 hr of medium and large storms (SA4) were compared for annual average flow, annual average concentration and annual load as in Figure 4.14. SA2 is a random sampling that does not respond to the corresponding time of storms. SA3 and SA4 are distinct from SA2 in terms of recorded time of sampling. In SA3, samples were taken within 6 hrs after the commencement of rain, but it does not take account of the influencing storm size, whereas in SA4, grab samples were taken within 6 hrs of medium and large storm events as recommended for grab sampling by Lee et al. (2007) and

Khan et al. (2006). The volume of total runoff is calculated based on runoff coefficient, catchment area and runoff depth.

As already mentioned, the volume weighted estimation of flowrate and annual loads using data from SA1 sampling method are close to SWMM simulated results. Based on the predictive capabilities of the developed model and suggestion from Leecaster et al. (2002), the time weighted sampling with volume weighted calculation can be assumed to have less error. For analysis of sampling approaches, it was considered as actual load. Random sampling (SA2) often developed low estimates, even less than half flow and 2/3 loads. It seems that this approach grabbed samples during small rainfall or baseflows. Compared to other sampling approaches, SA4 with mean estimation is nearer to actual flow, TSS and TP. Nevertheless, this approach has limitations in



Baseflow and simulated: SWMM outputs, SA1: time weighted sampling and SA2: random grab sampling, SA3: grab sampling within 6 hr irrespective of storm size and SA4: grab sampling within 6 hr of medium and large storms

Figure 4.14 *Comparison of simulated annual average flow and loads with four different sampling campaigns* identifying medium and large storms because the storm size before the end of rainfall is hard to determine. Alternatively, samples taken in SA3 can be used after the storm details are retrieved. Due to difficulties in performing SA4, SA3 is a suitable sampling approach that assists in finding the samples of medium and large storms within 6 hrs after the start of rainfall; however, this requires rainfall data, time of sampling and a greater number of samples than SA4.

In evaluating the sampling approaches, the concluding remarks is when the grab sampling is applied; it should focus on the medium and large events within 6 hr of storm commencement to obtain better mass estimations.

Contribution of DCIA on impervious land use

The directly connected impervious area or DCIA portion in the effective impervious area was found to be very important for producing runoff and loads, as in Figure 4.15, as the runoff and quality output from this part of imperivous area are 80.1 % peak flow, 75.1 % total runoff volume, 70.5 % TSS and 66.1 % for TP. The area of DCIA was determined to be 26.8 % of the total land use area (from Table 3.3). The DCIA road area and commercial roof occupy nearly 77 % of the total effective impervious area. Therefore, DCIA roads and roofs have a higher contribution to the runoff and pollution load. Nevertheless, the overall runoff coefficient is found to be less at 0.18. Most of the areas are either pervious or not connected to storm drainage. It is about 73.2 % of the total area.

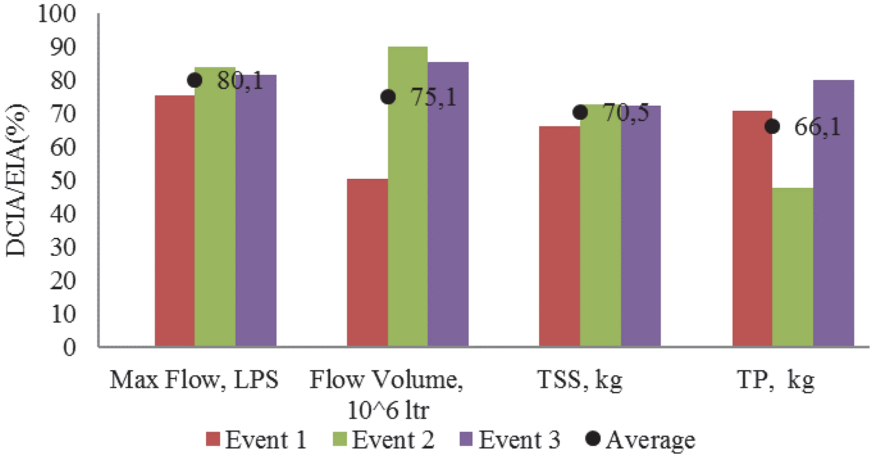
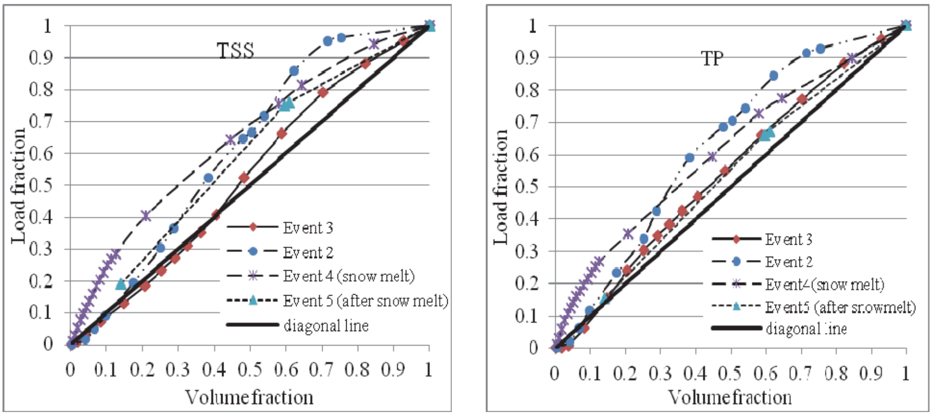


Figure 4.15 *Contribution of DCIA on impervious land use*

To conclude, the imperviousness is lower at 19.7 % due to abundant pervious land cover. However, the impact of DCIA, in particular roads and roofs, that have a relatively lower area significantly impacts runoff production up to 75 % and loads up to 66 to 71 %.

First flush

Whether implementing stormwater treatment measures to control the initial portion of runoff as specified by HELCOM recommendation is effective or not, the first flush phenonmenon for the measured four storm events was analysed as described by Bertrand-Krajewski et al. (1998). Figure 4.16 was plotted with the cumulative fraction of TSS and TP against the cumulative fraction of runoff volume. The deviation above the diagonal line indicates higher load during storm runoff (Lee et al, 2004), but for the intensity of the first flush, measurement was followed according to Nazahiyah et al. (2007) and Temprano et al. (2006), in which the pollution load swept along by 30 % of the volume was measured. The degree of first flush for event 2, event 3 and event 5 are not high, but after 40 % of runoff volume, the deviation from the diagonal line is clear, suggesting that flushing of the pollutant load is higher in a later portion within 60 % of storm runoff. ADD was less influential than the intensity of rainfall. There were studies that show the first flush has not been observed in relatively pervious areas (Maestre & Pitt, 2005) or the effect can occur at the end of an event (McCarthy, 2009). In contrast, the snowmelt event as in event 4 has a higher influence of first flush at 50 % for TSS and 45 % for TP. Lee et al. (2004) suggested that a seasonal first flush can occur in most of the cases. Before event 4, there was an extensive period of negative temperature and pollutant was accumulated with the snow packing, which was washed off after the temperature became positive during this event. Therefore, the control of stormwater pollution load at the initial portion cannot be ensured unless it is snowmelt runoff. It needs further investigation in terms of first flush before implementing control techniques.



Event 2: September 2014 with ADD 2.6 days, Event 3: 4–5 December 2015 with ADD 1.5 days, Event 4: 26–28 January 2016 during snow melt period and Event5: 9 January–1 February 2016 immediate after snow melt

Figure 4.16 *First flush phenomenon for TSS (left) and TP (right)*

To sum up, the treatment measures at the initial portion of runoff seemed to be less important than the later 60 % of the runoff for pollution load discharging, since the first flush at the initial stage was suppressed during the observed storm events. The opposite result was obtained for the snowmelt period. However, the analysed storm events are few and this conclusion needs further investigation.

4.5. Further Discussion

In the above individual results sections, the findings are illustrated and compared with previous studies. In this section, the limitations of the study and implications for further study as well as implications in practice will be discussed.

4.5.1. Limitations and further research

During the data processing for studying status of stormwater in Tallinn city, the data variation in most of the parameters was found to be high but this is a usual condition in stormwater monitoring. However, some parameters e.g. microbiological parameter, flow rate, etc. have few numbers of observations, which increase uncertainty in the results. Similarly, the data set did not have records for many storm events, which has resulted in low runoffs, particularly in the summer and autumn months. This has affected the quantity of runoff and concentrations during seasonal variation (Figure 4.7 and Figure 4.8). Obtaining large observations is costly. Therefore, it is recommended to perform a suitable sampling programme to obtain high accuracy in the quality and quantity of stormwater. Microbiological parameters have unavoidable impacts on stormwater and this demands a robust sampling programme that measures those parameters.

All the observations were at the outfalls or end of the drainage sytem. The study lacks the stormwater dynamics between the start and end of discharges, e.g the sources of pollution, pollutant transformation during travel time, self purification, illegal sewage connection, etc. Therefore, the potential causes of increase in pH, particularly in Härjapea, cannot be ensured and require further investigation. It is recommended to perform sampling programmes at different points along the drainge route to determine the actual source of pollution through differential analysis.

In the field of monitoring, passive sampling and online monitoring system have been increasing in attention, but reviews on these methods in this study are not covered. The study was based on the research reviews and has compiled the effective approaches; however, the uncertainties are not analysed through statistical measures. The real cost is not incorporated in analysing affordability; thus, there is a possibility of futher study to provide cost-based scenarios. The optimal sampling programme, though containing cost effective methods, does not provide higher certainty in all cases. Another recommendation is to evaluate the proposed sampling programme being implemented in a pilot basin.

In model development, the quality calibration and validation lacked observations, which has limited the application of the model when high accuracy is required. Calibration and validation using more quality observations will strengthen the quality performance of the model. The model is for stormflow routing and snow effect is not considered due to less available data. It is revealed that the first flush exists during snowmelt period. It has a considerable impact on runoff and pollution load. It will be interesting to simulate snowmelt once there are sufficient input parameters and observations. Our study is limited to SS and TP because the parameters e.g BOD, TP, microbilogical parameters and HC (Figure 4.5), can be correlated with SS. Nevertheless, the heavy metals and TN are also important parameters in stormwater. Heavy metals legislation is stricter now and there is a need to pay special attention to the monitoring of them, despite the fact that there was not an acute problem found during our study in Mustoja basin. It is recommended to use the model to further analyse these parameters in order to detemine the loads and their impacts.

The result about the first flush contradicted our assumption because the initial portion of runoff is less important than the later portion in the observed storms. This is a crucial result but it needs more data to strengthen the conclusion. Therefore, it is recommended to sample more storm events to cover all weather conditions.

4.5.2. Implication in practice

The study has beneficial aspects for developing an effective stormwater strategy because the status of stormwater as well as the trends provides the information about the potential parameters with the potential sites so that stormwater management can be focussed on effective control approaches. For instance, Tallinn seems to have potential parameters of TSS, TP, pH and microbiological parameters and the potential sites are Härjapea for TP and pH, most of the basins for SS (Table 4.2), and Lasnamäe, Pirita and Rocca al Mare for microbiological parameters (Figure 4.2). Moreover, the seasonal variation revealed at the end of winter and start of spring would be a crucial time for controlling pollutants. However, it is uncertain for the summer and autumn. The relationship between parameters are applicable in regression analysis, model development and load estimations. For example, SS can be interacted with BOD, TP, HC and microbiological parameters. The proposed sampling programmes can help in the starting phase of monitoring to conceptualise monitoring process. The study provides decision capability in selecting the suitable monitoring programme in terms of effectiveness, applicability and affordability so that it can be used to obtain coherent data about stormwater, which will be helpful to plan design and manage urban stormwater. The alternative approach to access the information about stormwater is modelling.

Modelling has proven to be effective tool in estimating runoff, EMCs and mass loads when there is limited resources and data availability. It is also possible to detect the potential land uses where the measures can be concentrated. Developing a sampling programme and model could be a good example for the Tallinn development plan and stormwater strategy. Water companies, city development units and monitoring units will benefit from the above mentioned applications of this study.

5. CONCLUSIONS AND RECOMMENDATIONS

Increased urbanisation and intense rainfall have been deteriorating water resources and flooding issues in urban areas. In the Baltic countries, runoff volume, pollution load and eutrophication have been problems for the past two decades, where Tallinn also discharges runoff into the Baltic sea. EU directives, HELCOM recommendations and national acts and regulations have emphasised the need to improve the stormwater quality and control of runoff. As Tallinn is in the early stages of implementing a stormwater strategy, it has initiated some stormwater solutions, but it still needs the clear picture of stormwater dynamics. Quality data is the basis for implementing stormwater management solutions. To this end, the development of a monitoring programme and basin wise modelling are the activities planned in strategic documents. Our study is related to this action plan, where it first investigates the stormwater status in Tallinn city, accesses the change in stormwater concentration over the year, searches for the best monitoring practices and finally develops a model for a pilot basin in Tallinn. The requirements of national and international regulations have triggered the components to initiate stormwater investigations and solutions. Their continuation is important for the long-term, since the impact of a stormwater pollution load is not intermittant. More certainty in the information about stormwater status through appropriate monitoring and modelling will ensure the effectiveness of the solutions to be applied in stormwater management.

- Our research results about the quality and quantity of Tallinn stormwater showed that the measured concentrations of most of the parameters are below the national limit values (*Paper I*) and statistically significant decreasing trends are detected (*Paper II*). The results are similar to the monitoring results of the responsible authorities. This study revealed that the variability of several parameters, microbiological indicators, suspended solids, etc., is high. The analysis showed that there is a seasonal cycle in stormwater parameter dynamics. Insufficient data on entire rainfall, absence of first flush information and high variability of data and data quality are particular shortcomings in the ongoing monitoring programme.
- From Paper I and II, the general status of stormwater condition is understood. The question of data representativeness was raised and we proceeded first to compare the sampling approach applied to the other best-practiced approaches mentioned in various analyses. Several papers agreed that grab sampling had higher uncertainty in results and difficulties to provide EMCs and mass load. A review on sampling approaches aimed to get different options on sampling methods because a single robust approach

will not be suitable for all conditions, especially when there is resource constraint. Therefore, we provided a suitable monitoring programme and ultimately endeavoured to recommend an effective and optimal sampling programme for Tallinn. A sampling method with two processes – one with an intensive and the other with an extensive monitoring method – are proposed (*Paper III*). The applicability of this recommended approach is compared with approaches in use by neighbouring countries and found that progressively, they are also practicing the comprehensive approaches. We conducted this study for developing a suitable monitoring programme that assists in designing the early stage of monitoring. The proposed monitoring programme can be a part of the accomplishment of the action plan mentioned in Tallinn Development plan and Tallinn Stormwater Strategy 2030.

- In Paper IV, another approach to modelling based on basin is assessed. The model performance was good for runoff estimation. Even the predictive capability of quality is moderate. Sensitivity analysis shows that the model is sensitive to imperviousness percentage. During the investigation of Mustoja stormwater basin, we found that the impervious areas percentage, 19.7 %, is lower than was expected, which suggest that the large basin with the mixed land use has a different overall runoff coefficient than small basins. By applying the national standard of runoff coefficient, the overall imperviousness was found to be 44 %, and this coefficient is nearly 2.3 times higher. This will give a higher runoff and pollution load. For the mixed land use and large basin, the runoff coefficient requires modification based on exact detail land cover and soil to calculate precise runoff. Directly connected roads and roofs to drainage systems are potential elements for applying source control techniques as the surface flow generated on them significantly impacts runoff production by up to 75 %, and loads by up to 66 to 71 %. Therefore, the effective solution to reduce the discharge will be the isolation of runoff from main roads and commercial building roofs, e.g. diverting to detention or retention ponds, stormwater harvesting, porous pavement, rain gardens, bio-swales alongside the roads, etc. and rainwater harvesting in commercial buildings and houses.
- To improve the practised grab sampling, our study suggests taking the sample within 6 hr of storm commencement to estimate near the actual load. Also, mostly medium and large storm events have to be sampled (*Paper IV*).
- Model development provided the stormwater dynamics of the studied basin and this approach could be a good alternative in estimating actual concentrations and loads at limited resources that provide a basis for appropriate treatment measures to be introduced.

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ABSTRACT

Runoff and pollutant load from urban stormwater have been deteriorating waterbodies. In order to protect and improve the ecological status of seawaters, EU Directives, HELCOM and Estonian regulations have set requirements and initiated action plans through regional and local government. The status of stormwater should be updated at all times before, during and after implementation of treatment measures, but collecting representative data is a challenging task as it is always associated with uncertainties. Insufficient and weak data can mislead the decisions about sustainable planning, designing and policy formulation.

This study aimed to provide status of stormwater quality and quantity through the statistical assessment of measured and available data, thereafter assessing the trends over short term (10 years) and long term (18 to 19 years) periods. Uncertainty and accuracy in the data set was measured using coefficient of variance and relative standard error. Futhermore, it aimed to provide the approaches to access the representative data, stormwater dynamics, mean concentration and pollution loads. One approach is proposed based on a review of best practiced monitoring programmes, and another approach is model development based on pilot basin.

The results about quality and quantity in Tallinn stomwater shows the measured concentrations of most of the parameters are below limiting values, and they are in decreasing trends. Street sweeping, sewer network improvement and the decline in suburban agriculture areas are the effective causes for this decrease. Nevertheless, pH, SS, TP and microbilogical parameters need more attention. pH in 2/7 basins have significant and 5/7 basins have less significant upward trends. The 90th percentile of SS exceeds the national limit of 40 mg/l several times (17.9 %) whereas 90th percentile TP can reach the limit value of 1mg/l in a few basins; Härjapea has an increasing trend at $p=0.051$.

SS can be moderately correlated with BOD (CC: 0.33−0.60), TP (CC:0.19−0.54), microbiological parameters and HC, and weakly with TN, DO and conductivity. A higher degree of relationship more than 0.6 were found for BOD−TP and microbioligical parameters with BOD, TP and TN.

Uncertainty of the mean concentration is high if the number of samples taken is less and it is a challenging task to obtain high certainty with a few samples. Two approaches are discussed for acquiring representative data and near accurate stormwater dynamics.

In the first approach, reviewing best practiced monitoring programmes, a suitable sampling approaches to obtain coherent stormwater data are deducted to provide options to choose the one that balances affordability and effectiveness. An optimal sampling programme is proposed considering the local conditions and constraints, and it is recommended for the Tallinn catchment area.

Model development, an alternative approach of acquiring stormwater dynamics at limited data resources, is found to be accurate for runoff prediction and moderate capability for quality prediction. In applying this model, additional results about imperviousness, effective directly connected impervious area (DCIA), first flush and sampling approach are discovered. Imperviousness for Mustoja basin after model calibration was found to be only 19.7 %, which is lower than the imperviousness (44%) estimated using the runoff coefficient of the national standard. DCIA, especially roads and roofs, which have relatively lower area, produce a significant amount of runoff of up to 75 % and loads of up to 66 % TN and 71 % TP. The treatment measures concentrating roads and roofs will reduce stormwater impacts considerably, whereas the first flush results show that the initial portion of runoff is less important than the later 60 % of runoff for the observed events, suggesting that the treatment measures to address the initial runoff may be less effective.

Finally, whenever grab sampling has to be performed for stormwater monitoring, it should focus on the medium and large events within 6 hr of storm commencement to obtain data for more effective mass estimations.

The study endeavoured to propose the sampling programme and an example of model development with an illustration of its application that provides some solutions in stormwater management. The study outcome about stormwater status and approaches will be helpful for state authorities, water managers and water companies to use them in improving stormwater management strategies, planning and designing an effective data collection system, as well as implementing stormwater treatment measures. Moreover, it helps to obtain more coherent and reliable information about stormwater quality and quantity and enhances the decision capability for sustainable planning, designing and policy formulation.

KOKKUVÕTE

Linna sademevesi ja selle äravoolust tingitud reostuskoormus on halvendanud veekogude seisundit. Merevee kaitsmiseks ja selle ökoloogilise seisundi parandamiseks on ELi direktiiv, HELCOM ja Eesti õigusaktid sätestanud nõuded ning on algatatud piirkondlike ja kohalike omavalitsuste tegevuskavade koostamine. Tegevuskavade aluseks on esinduslikud sademevee andmed, kuid nende andmete kogumine on raske ülesanne, sest sellega kaasneb alati määramatus. Ebapiisavad ja puudulikud andmed võivad põhjustada eksitavaid otsuseid jätkusuutlikul planeerimisel, projekteerimisel ja poliitika kujundamisel.

Selle uuringu eesmärk on esitada infot sademevee omaduste ja koguste kohta olemasolevate ja uute seireandmete statistilise hindamise teel ning uurida lühiajalisi (10 aastat) ja pikaajalisi (18–19 aastat) suundumusi. Andmekogumi määramatuse ja täpsuse iseloomustamiseks kasutati variatsiooni koefitsienti ja suhtelist standardviga. Peale selle on eesmärgiks leida võimalused esinduslike andmete saamiseks ning sademevee dünaamika, keskmise kontsentratsiooni ja reostuskoormuse hindamiseks. Vaadati üle seireprogrammide parim tava ja arendati pilootvalglal veeseiret ja sademeveemudelit.

Tallinna sademevee äravoolu ja kvaliteedi andmed näitavad, et enamiku näitajate sisaldused on lubatud piirväärtustest väiksemad ning on täheldatav mitmete näitajate vähenemas. Eelkõige on vähenemise põhjuseks paranenud heakord tänavatel, kanalisatsioonivõrgu uuendamine ja tootmise vähenemine linnalähedastes põllumajanduspiirkondades. Sellele vaatamata vajavad pH, heljum, üldfosfor ja mikrobioloogilised näitajad rohkem tähelepanu. pH tõusutrend on 2/7 valglatest statistiliselt oluline ja 5/7 valglatest vähem oluline. Heljumisisalduse 90. protsentiili väärtus on ületanud riiklikku piirnormi 40 mg/l mitmel korral (17,9%), samas kui üldfosforisisalduse 90. protsentiili väärtus on mitmel valglal jõudnud piirväärtuseni 1 mg/l. Härjapea jões on üldfosfori suundumus tõusev ($p = 0,051$).

Heljum korreleerub mõõdukalt biokeemilise hapnikutarbega (korrelatsioonikoefitsient 0,33−0,60), üldfosforiga (korrelatsioonikoefitsient 0,19−0,54), mikrobioloogiliste parameetritega ning naftasaadustega ja nõrgalt üldlämmastikuga, lahustunud hapnikuga ja elektrijuhtivusega. Tugevamat korrellatiivset seost (korrelatsioonikoefitsient suurem kui 0,6) täheldati biokeemilise hapnikutarbe ja üldfosfori vahel ning mikrobioloogiliste parameetrite ja biokeemilise hapnikutarbe, üldfosfori ja üldlämmastiku vahel.

Väheste võetud proovide korral on keskmise kontsentratsiooni määramatus suur. Väikese määramatuse saavutamine mõne prooviga on problemaatiline ülesanne. On vaadeldud kaht lähenemisviisi esinduslike andmete saamiseks ja võimalikult täpseks sademevee dünaamika hindamiseks.

Seireprogrammide parima tava ülevaatuse käigus esitati sobivad proovivõtumeetodid sademevee sidusate andmete saamiseks ja võimalused taskukohasuse ja seiretõhususe tasakaalustamiseks. On välja pakutud Tallinna linna sademevee valglale soovitatav optimaalne proovivõtuprogramm, mis võtab arvesse kohalikke iseärasusi ja piiranguid.

Modelleerimine näitas, et ebaühtlase andmemahu jaoks väljatöötatud mudeliga sademevee dünaamika hindamiseks on võimalik ennustada äravoolu üsna suure täpsusega ja vee kvaliteeti mõõduka täpsusega. Selle mudeli kasutamisel saadi täiendavat teavet kõvakattega pindadelt sademevee äravoolu, kvaliteedi ja äravoolutegurite kohta. Kõvakattega aladelt otse kanalisatsiooni juhitud sademevesi teedelt ja suhteliselt väikese pindalaga katustelt, moodustab kuni 75% äravoolust ja kuni 66% üldlämmastiku- ja 71% üldfosfori koormusest. Teedele ja katustele keskendatud puhastusmeetmed vähendavad sademevee mõju oluliselt, samas kui tulemustest on näha, et vaadeldud sündmuste korral on äravoolu esimene osa vähemolulisem kui viimane 60%.

Kui sademevee seirel tuleb kasutada punktproovide võtmist, peaks seire, sademevee äravoolu kohta paremate andmete saamiseks, keskenduma keskmise ja suure intensiivsusega sademete perioodidele ja seire peaks toimuma 6 tunni jooksul saju algusest.

Uuring pakub sademevee äravoolu korraldamiseks lahendused optimaalse proovivõtuprogrammi koostamiseks. Eksperimentaaluuringud võimaldasid välja töötada sademevee äravoolu ka kvaliteedi mudeli Mustoja valgala näitel. Uuringu tulemused aitavad riiklikel ametkondadel, veemajandusspetsialistidel ja vee-ettevõtetel arendada sademevee haldamise strateegiaid, planeerida ja kavandada tõhusaid andmekogumissüsteeme ning valida sobivaid sademevee puhastamise meetmeid. Peale selle aitavad uuringu tulemused saada usaldusväärsemat ja ühtsemat teavet sademevee koguste ja kvaliteedi kohta ning aidata kaasa jätkusuutliku planeerimise, projekteerimise ja poliitika kujundamise otsuste tegemisele.

APPENDIX I ORIGINAL PUBLICATIONS

PAPER I

Paper I: Maharjan, B., Pachel, K., Loigu, E., 2013. *Urban stormwater quality and quantity in the city of Tallinn.* European Scientific Journal, 3, 365-375.

URBAN STORMWATER QUALITY AND QUANTITY IN THE CITY OF TALLINN

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Abstract:

This study aimed to provide an overview of stormwater quality and quantity, the impact on waterbodies and the likelihood of its usage in stormwater management. The potential impacts were assessed using statistical analysis following HELCOM, EU Directive and Estonian requirements. Further, Seasonal behaviour, variability, tentative sample size and frequency were examined using strongly dependent parameters obtained from correlation studies. Results show that the average concentrations of pollutants are not extremely high except microbiological parameters. Most basins have positive correlation of 0.4 - 0.6 between flow and suspended solids (SS), as well as of 0.4 - 0.95 between total phosphorus (TP) and SS. As for seasonal variation, large amount of SS is transported in spring whereas in summer, runoff and SS are consistent against winter and autumn. However, at a 70% confidence interval, there is considerable uncertainty in the mean flow and concentrations. Flow and SS have higher uncertainty than conductivity, BOD7, total nitrogen (TN) and TP. It was discovered that most of the samples belong to a small range of daily rainfall (<5 mm) and there is no measurement for first flush. Variability and inadequate representation of rainfall range calls for comprehensive sampling and validation of the data intended to use in stormwater management programs.

Key Words: Urban stormwater, pollution load, monitoring program, seasonal variation

Introduction

Urbanisation with its uncontrolled impervious surfaces increases stormwater runoff and transports pollutants to the receiving waterbodies. These pollutants not only have an adverse effect on human health but also to indigenous plants and animals (Jacobson, 2011; Christensen et al., 2006; Leecaster et al., 2002). Sediment from stormwater runoff is a potential problem source (Lau & Stenstrom, 2005; German & Svensson, 2002). In order to prevent and minimise stormwater runoff volumes and the pollution load, the Baltic Sea member states jointly pooled their efforts through the Helsinki Commission towards the ecological restoration of the Baltic Sea (HELCOM, 2002). Furthermore, the EU Water Framework Directive (WFD) as well as the Estonian Water Act (EWA) (RTI, 2011) have set a target to protect all waters against pollution and to achieve the good status of all waters by promoting sustainable water and wastewater management (EC, 2000).

The eutrophication of inland waters and the sea is one of the major environmental problems in the Baltic Sea Region, including Estonia (Kotta et al., 2009; Iital et al., 2010; Elofsson, 2010). The urban runoff load has made a substantial contribution towards raising nutrient levels in waterbodies (Taylor et al., 2005; King et al., 2007). HELCOM has adopted an action plan to considerably reduce the anthropogenic nutrient load by 2021 (HELCOM, 2007).

The revised Environmental Charges Act (RTI, 2005) did not elicit the expected reduction in pollutant discharge into waterbodies because the stormwater pollution load is not easily measurable. The stormwater load measurement expenses are significantly higher than the collected tax returns. The specialists in the Ministry of the Environment had not yet defined exactly what kind of mean concentration should be measured (Lääne & Reisner, 2011). There is real need to study urban stormwater pollution in order to develop methods for the reduction of stormwater pollution exports to the sea (Hood et al., 2007), including both flood control and pollution control.

To address these problems and to select appropriate water protection measures, the first objective that needs to be set is to activate the assessment of the status of water, including a comprehensive interpretation of the monitoring data that form the basis for the planning and implementation of protection measures. In addition, low variable and representative data are standard requirements for stormwater management approaches, as they are susceptible to the actual total pollution load and the mean concentration of pollutants. This study will provide a status update on stormwater quality and quantity in the city of Tallinn through analysis of the monitoring data. The main objectives of the study are to assess stormwater quality and quantity; the spatial and seasonal variation of stormwater discharges and pollution load; and to identify, the likelihood of data to be meaningful, representative and verifiable quality on the basis of existing routine monitoring programme, so that they can effectively aid in managing stormwater runoff.

Material and Method

Site Description

Tallinn, the capital of Estonia, is situated on the southern coast of the Gulf of Finland, in north-western Estonia. It has total area of 156 sq km with a population of 417,741, and population density of 2,614 per sq km. The average precipitation in Estonia is 550–750 mm and the mean runoff 280–290 mm per year. The climate in Tallinn is fairly cold in winter with an average temperature of 1.93 °C and a maximum low of -32 °C, a cool spring with little precipitation, a moderately warm summer with an average temperature of 8.64 °C and a high of 32.3 °C, and a rainy autumn.

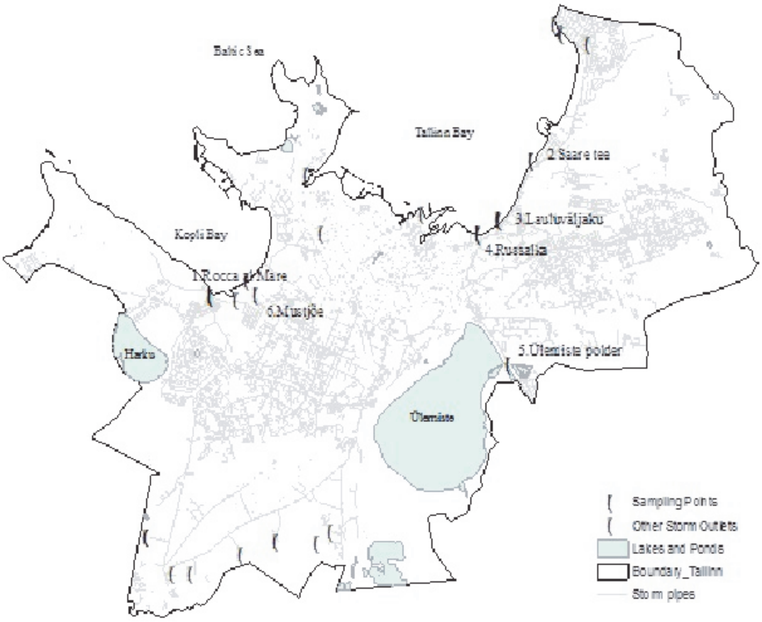

Figure 1: Sampling sites and their location in Tallinn

The area of the stormwater system of Tallinn is about 6,500 hectares and the length of stormwater conduits was 414 km in 2011 (Tallinna Vesi, 2012). Stormwater from residential and industrial areas is either diverted to municipal Waste Water Treatment Plants (WWTPs) and treated with sewage or is collected in a separate stormwater system and mainly disposed to waterbodies without any treatment. The city centre has a combined sewerage system while the other parts have mostly separate systems. There are 23 stormwater outlets that mostly discharge water to the coastal sea (*Figure 1*) in the Tallinn catchment area. Six major storm outlets: Rocca al Mare, Saare Tee, Lauluväljak, Russalka, Ülemiste and Mustoja are included in the monitoring program organised by the Tallinn City Environment Department. For this study, these six outlets are examined, between them covering a catchment area of almost 4,000 ha, as they are supposed to form a separate stormwater system in Tallinn city. Among them, the Mustoja outlet is the largest and serves almost 30% of the total area. The second biggest is Lauluväljak and the smallest is Saare tee (*Table 1*).

Table 1: Area of Drainage basins and their characteristics

No.	Basin	Area, ha	% Coverage	Receiving water body	Characteristics
1	Rocca al Mare	816	21.5	Kopli Bay	mostly storm and surplus water from the apartment house areas, from pools in the zoo during water exchange, an increase in impervious areas is noticed in the catchment.
2	Saare tee	156	4.1	Tallinn Bay	storm and drainage waters from private house area, collected via open ditches and Varsaallika spring (basin 1.6 km^2), sewage discharges from the private house area can occur
3	Lauluväljak	961	25.3	Tallinn Bay	mostly high density area with impervious area one third of total area. Runoff collected from residential and industrial, sewage discharges can occur from this area
4	Russalka	734	19.3	Tallinn Bay	mostly consists of the Ülemiste polder storm and drainage waters and Lake Ülemiste surplus water after heavy and continuous rains, and during the meltwater period
5	Ülemiste polder			Tallinn Bay	storm and drainage waters from the industrial district and private house areas, airport treated stormwater and runway stormwaters, Ülemiste polder drainage water
6	Mustoja Paldiski Road	1,128	29.7	Kopli Bay	mostly storm and drainage waters from private house areas, apartment houses and industrial district collected via ditches, open channels and pipes into the Mustoja River, increase in impervious areas is noticed in the catchment, sewage discharges from one of the private house areas can occur
	Total	**3,795**			

Data source, sampling procedure and chemical analysis

Stormwater monitoring has been carried out since the late 1980s, but it only became regular in the 1990s. For this study, stormwater monitoring data for the years 2005 and 2008-2011 have been obtained from monitoring reports (Pauklin et al., 2005-2011). In this monitoring system, grab samples were collected 4–6 times a year from the stormwater outlets (see *Figure 1*). The data was measured only once in 2010. The sampling procedure adhered to the sampling requirements in Council Regulation no. 30, 5 May 2002, of the Estonian Ministry of Environment. For 2012, samples were measured by both Tallinn University of Technology and AS Tallinna Vesi. Other samples were taken by the Estonian Environmental Research Centre, all of which are competent bodies according to EN ISO/IEC 17025:2005 for conducting tests in the field of water analysis (accreditation scope on the Estonian Accreditation Centre). Data for 24 hour precipitation from the Tallinn-Harku Meteorological Station located approximately 20 km from the study area was obtained from the Estonian Meteorological and Hydrological Institute (EMHI) for 2005–2012. Samples were tested for parameters such as conductivity, pH, temperature, suspended solids (SS), total nitrogen (TN), total phosphorus (TP), biological oxygen demand (BOD_7), hydrocarbons (HC), Escherichia Coli and Enterococci using analytical methods based on ISO 10523, ISO 5667-10, EVS-EN 25814, EVS-EN 27888, EVS-EN 872, ISO 5815-1, SFS 5505, EVS 9377-2, EVS 9308-1, EVS-EN ISO 7899-2 and EVS-ISO 6340, respectively.

Data Analysis

Normal statistical analysis was carried out to estimate arithmetic means, median, quartiles, correlation coefficient, coefficient of variance (CV) and confidence intervals (CI). The relationship between parameters were analysed through correlation coefficient to obtain prior parameters according to which seasonal variation were observed. Further, with CV and CIs, it was attempted to assess variability of data. Finally, variability and representativeness of data to rainfall intensity were scrutinized through sample size and frequency.

The grab samples for a year did not amount to more than six, except for Mustoja (consists 12 in 2005). It was known from rainfall data of the available data source period that the main parameter of hydrology (average annual rainfall) did not vary significantly .The highest deviation from the mean was 18% only in 2005. Thus, these samples from six years for each basin were combined to attain a higher number of samples, assuming that there was no excessive change in the urban environment.

In terms of the estimation of average total mass emission, it is viable to measure grab sampling with continuous flow measurements over a specific time period (day, week, month), instead of instantaneous flow measurement (Fogle et al., 2003; HELCOM, 2006). For instantaneous flow and concentration measurement, the load calculation was carried out by multiplying the average load by 365 days. Therefore, the mean flow and load over six years in each basin were deemed the average annual flows and loads that are discharged into the waterbodies.

To analyse seasonal variation, the twelve months were categorised with regard to the hydrological year as spring (February, March and April), summer (May, June and July), autumn (August, September and October) and winter (November, December and January). In this way, the data were separated according to the sampling date and grouped into 4 seasons irrespective of yearly variation.

Sampling time during a storm event affects runoff. With correct sampling frequency, it avoids the bias of the first flush and better characterises the mass emission of the event (Lee et al., 2007). To evaluate the sampling programme in terms of sampling number and frequency, it was assumed that there was a constant area of impervious surfaces throughout the study period so that flow can be mainly related to rainfall intensity, though the correlation between daily rainfall intensity (DRI) and runoff was 0.64. Snow cover period was separated and excluded from the analysis because snow melt affects hydrology in a different way. The rainfall data was stratified into three sizes according to rainfall range (small: <5 mm, medium: 5–20 mm, and large: >20 mm). The number of samples that can address rainfall range is hard to determine in regard to grab samples because a grab sample is taken at a particular flow and time, and finding the rainfall intensity that generates that particular flow is almost impossible. Therefore, approximate DRI according to minimum and maximum flow was sought from 24 hour precipitation data. Then the rainfall for other discharges was interpolated to put into the range, and the amount of rainfall within that range was calculated. This rainfall number is actually the number of samples within that particular range. After comparing with the required number of samples, the percentage deficit and surplus was calculated.

Result and Discussion

Stormwater general statistics

The flow and pollution parameters from sampling for six years at six stormwater outlets are summarised in *Table 2*. The total number of samples for most of the parameters is 156. However, some have a lesser number than that to calculate mean flow and mean concentration. HELCOM and Regulation No 269 of the Government of Estonia, 31 July 2001, on the procedure for discharging wastewater into waterbodies or soil, provided limiting values for SS as 40 mg/l and HC as 5 mg/l in stormwater runoff (RTI, 2001). The European Union, as well as Estonia, has restricted microbiological parameters exceeding 1000 cfu/100ml Escherichia Coli and 400 cfu/100ml Enterococci for good bathing water quality (EU, 2006; RTI, 2008). There are three public beaches on the Tallinn coastline that are not far from the stormwater outlets. The ecological status of the Tallinn coastal sea was estimated as moderate (The Estonian Environment, 2012). The trophic level in the coastal sea is still quite high despite the fact that the pollution load of Tallinn WWTPs has decreased remarkably since 1990 and discharges via deep outlets do not extend to the coast; therefore, stormwater is still affecting the coastal sea.

It is noticeable that there is large variation in flow, conductivity, SS, TN, TP and pathogens. There is a higher consistency of pH that falls near the neutral range, implying that there is negligible impact from any kinds of industries. Even extreme pH values vary between 6 and 9, and lower or higher values that exceed the limits can be toxic to aquatic organisms. Saare Tee (sampling point 2) has the lowest but Mustoja (sampling point 6) has the largest flow. It reflects the fact that outflows at Saare Tee are from a small drainage basin and at Mustoja from a large drainage basin. It is also true the Russalka (sampling point 4) sometimes exceeds the runoff of the Mustoja basin. In such a case, the runoff is most likely due to the captured overflows of Ülemiste Lake during storm events.

The observed pollutant concentrations are not substantially high, excluding microbiological parameters. The mean concentration for SS is below the permissible level of 40 mg/l. Comparing flow with the transport of this pollutant, the results are found to be opposite in the case of Saare Tee. The discharge from Saare Tee is more concentrated than Mustoja. But in the case of Mustoja basin, there is a high variation in the measurement of SS. Higher readings are recorded occasionally; therefore, the maximum discharge is more than twice the mean value. Rocca al Mare (sampling point 1) is the most polluted basin in terms of mean SS. The basin has water exchange activities inside. This is probably the major contributing factor for such a large value. Ülemiste polder (sampling point 5) has natural stormwater treatment systems – polder areas – that treat stormwater and decrease the harmful effects on the receiving waterbodies. It is found that a few SS samples are above the limit of HELCOM and the Estonian stormwater requirement at 12.3%. The result shows that there are no significant effects from the SS discharged at the outlets of Lauluväljaku, Russalka and Ülemiste sites. However, this is hard to conclude for other sites because the maximum amount of these parameters is very high and it is essential to look at what factors affected those basins to cause such high values.

Table 2: Pollution parameters concentrations

S. Pt.		Q, l/s	Temp., °C	Diss.O, mgO/l	pH	Conduct. µs/cm	SS, mg/l	BOD$_7$, mgO/l	Ntot, mgN/l	Ptot, mgP/l	HC, mg/l	E. coli, CFU/100ml	Enterococcid, CFU/100ml
	Limit		40								5		
1	Samples	23	24	24	24	24	24	24	24	24	16	10	10
	mean	95.8	8.6	9.7	7.5	818.3	38.2	10.6	4.1	0.4	0.2	571,900	27,340
	range	22.9 - 244.2	3.1 - 15	4.2 - 16	7.11 - 8.09	39.5 - 1,556	3 - 178	1.9 - 41	1.94 - 7.21	0.18 - 1.4	0.02 - 1.31	14,000 - 5,100,000	4,800 - 56,000
2	Samples	24	24	24	24	24	24	21	24	24	0	10	10
	mean	38.4	8.9	9.3	7.7	1,420.5	22.8	6.9	4.6	0.4	NA	174,743	16,018
	range	2 - 188.7	3.5 - 14.7	2.5 - 15	7.2 - 8.01	82.9 - 7,600	2 - 220	1.9 - 23	2.72 - 7	0.17 - 1.37	NA	3,600 - 1,200,000	500 - 100,000
3	Samples	19	24	24	24	24	23	13	24	24	0	4	4
	mean	80.5	9.4	10.2	7.8	1,008.9	8.4	8.1	5.0	0.2	NA	92,775	11,150
	range	13.8 - 432.9	6 - 13.9	6.5 - 15	7.2 - 8.36	78.7 - 2,220	2 - 56	3 - 35	3.1 - 9.87	0.08 - 0.8	NA	3,800 - 240,000	1,700 - 21,000
4	Samples	26	26	26	26	26	23	25	26	26	0	10	10
	mean	150.0	10.3	9.8	7.9	760.5	18.3	9.1	6.8	0.1	NA	50,975	6,218
	range	23.4 - 724.5	2.5 - 16.5	0.5 -16.7	7.44 - 8.18	58.5 - 4,100	2 - 80	3.3 - 45	1.81 - 18	0.02 - 0.3	NA	1,350 - 320,000	160 - 46,000
5	Samples	4	26	26	26	26	21	19	26	26	0	10	10
	mean	115.9	5.8	7.4	7.4	596.0	6.2	7.9	7.5	0.1	NA	432	89
	range	37.1 - 334	0.5 - 19.5	0.2 - 18	7.09 - 7.82	55.5 - 1,015	2 - 17	2.3 - 37	1.07 - 45	0.02 - 0.41	NA	0 - 1,200	0 - 350
6	Samples	32	32	31	32	32	32	30	32	32	16	4	4
	mean	184.3	9.7	9.9	7.7	558.4	32.0	5.7	4.2	0.3	0.2	29,850	3,818
	range	108 - 450.2	4.9 - 14.7	4.7 - 16	7.16 - 8.08	41 - 1,279	2 - 416	1.4 - 21	2.6 - 9.64	0.08 - 2.2	0.03 - 0.69	3,400 - 5,1000	470 - 10,000

The mean concentration of dissolved oxygen in stormwater varies typically from 7.4 to 10.2 mg/l. However, the impact on the oxygen balance is important if secondary pollutants such as oxygen demanding sediments exist. All the measured values for HC are below the permit level and it implies there are no effects due to hydrocarbons in the waterbodies.

Nutrients are a major problem for eutrophication in the Baltic Sea and urban runoff and stormwater from Tallinn city have also added a considerable amount to the sea. The mean concentration of TN and phosphorus exceed the second class – good status limit values of natural surface water in all basins. The limit values are 3 mgN/l and 0.08 mgP/l respectively. However, as shown in *Table 2*, the total N and P concentration in stormwater are substantially less than those of treated wastewater. The limit values by special water permit for Tallinn WWTP outlet are 10 mgN/l and 1 mgP/l, respectively. Microbiology varies quite a lot, with the highest values occurring in the Rocca al Mare outlet, which consists of water from the pools of the zoo. It is possible that some sanitary waste in those basins mixes with runoffs.

Total mass emission

In many studies, the average mass emission from the catchment is estimated using EMC for which composite samples or numbers of grab samples over number of storm events are required. Selecting a single grab sample from many events provides a snapshot of water characteristics for each event, but it will not tell the entire story of the whole pollutograph for any one event. The value of single grab samples is sensitive to the point in time where the grab sample is made (Davis & McCuen, 2005). There is high uncertainty in the estimation of actual mass emission from the grab samples, but it is planned to provide a general overview of mass emission to determine amount of pollutants that are discharged from the specific outlet.

Table 3: Calculated average total mass and specific mass emission for the study period (2005–2012)

Sam. Pt.	Flow		SS		BOD7		Ntot		Ptot	
	Total th. m^3/yr	Specific l/s*ha	Total t/yr	Specific kg/ha	Total t/yr	Specific kg/ha	Total t/yr	Specific kg/ha	Total t/yr	Specific kg/ha
1	3,022.3	117.45	116.2	142.37	30.6	37.47	12.2	14.98	1.2	1.49
2	1,211.6	246.28	48.4	310.07	8.4	53.53	5.4	34.55	0.7	4.22
3	2,537.8	83.74	42.7	44.46	55.5	57.76	13.5	14.07	0.6	0.67
4	4,731.8	204.42	77.8	105.93	45.7	62.27	34.5	47.05	0.4	0.58
5	3,655.8		27.2		24.9		37.7		0.3	
6	5,813.0	163.41	303.8	269.30	38.5	34.16	24.7	21.86	2.1	1.82
	20,972.3		616.0		203.6		128.1		5.3	

Table 3 shows the mass emissions for each basin in terms of the total for and specific of the catchment area. Due to the unavailability of an actual area of the Ülemiste polder, the specific weights were not calculated. It is evident that, on average, Mustoja (sampling point 6) emits the highest SS

with the largest volume of runoff. The specific load of this basin is also comparatively large. In contrast, Saare Tee (sampling point 2) is a small basin and also emits small discharges. However, it has a large specific load for SS, BOD_7, nitrogen and phosphorus. Rocca al Mare (sampling point 1) is also a significant basin for SS, BOD_7, nitrogen and phosphorus, though it emits less pollution per hectare of area than Saare Tee. The highest specific load of BOD_7 and nitrogen is released from Russalka basin (sampling point 4). Lauluväljak and Ülemiste are mild in terms of their discharging pollutant load. The average amount of mass through these six basins is 616 t/yr of SS, 203.6 t/yr of BOD_7, 128.1 t/yr of TN and 5.3 t/yr of TP through 20,972 thousand cubic metres of runoff.

As conducted by AS Tallinna Vesi, the stormwater amounts and pollution loads are not measured but are calculated using a formula based on the drainage area and annual rainfall for annual reporting to the environmental authorities. These values are smaller than in *Table 3*. The possible reasons for this could be that the meteorological station is too far and does not adequately describe the actual situation in basins and the different methodological bases.

Correlation with flow and suspended solids

It is attempted to correlate runoff pollutants with flow at every discharge point, as shown in *Figure 2*. In all the sampling sites, SS and BOD_7 have positive correlation with discharge at that particular time of sampling, while other parameters show positive correlation at certain sampling sites and negative at other sites. The Lauluväljak and Mustoja basins have a good correlation of SS at nearly 0.6. Ülemiste and Saare tee have nearly 0.4, while the remaining basins have a relation of less than 0.4.

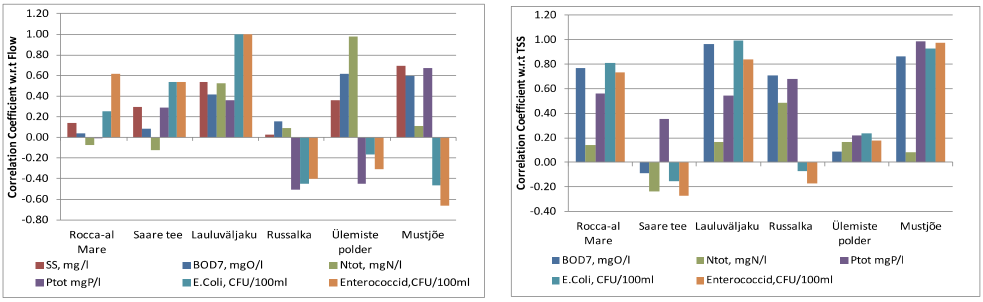

Figure 2: Correlation coefficients with respect to flow (left) and with respect to SS (right)

In relation to flow, parameters aside from SS do not have a strong one-sided correlation. As in the figure on the right, they are again correlated with SS and it is found that in three of the six sites (1, 3 and 6), parameters such as BOD_7, phosphorus and microbiological parameters have a strong positive relationship (range 0.5 - 0.95) with SS. Nutrients, especially TP, always show a positive increment with SS at correlation 0.4 - 0.95, though one site indicates a low figure at nearly 0.2. In the case of microbiological parameters, the Rocca al Mare, Lauluväljak and Mustoja basins are more sensitive to the amount of SS.

Seasonal variation

Normally, the rainy season results in a high amount of runoff from urban areas, while the dry season induces considerably low. Also, the ice melting period is very sensitive to a rise in water levels in drains and channels. During spring (see *Figure 3*), there is usually a high water depth in the conduits and channels. The spring runoff is mainly due to meltwater rather than rainfall, while the autumn and winter runoff is entirely due to precipitation. The mean runoffs at outlets are higher in the winter season than in autumn and summer. Viewing the range of runoff, it is also possible that a greater runoff can occur during autumn but the variability is high. Nevertheless, Russalka showed quite a high flow in winter. This is due to the fact that surplus water in Ülemiste Lake discharged into the overflow channel during heavy rainfall. Generally, summer is the low rain season.

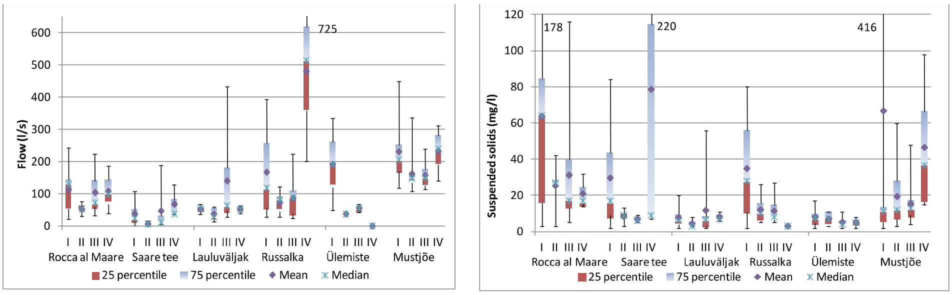

Figure 3: Variation of flow (left) and SS (right) for spring (I), summer (II), autumn (III) and winter (IV)

The emission of SS depends on storm event duration and intensity, antecedent dry days and impervious surfaces. Large storm events do not necessarily develop into a large amount of SS, but the first flush is the main concern in this regard (Davis & McCuen, 2005). *Figure 3* (right) shows that all basins discharge high SS during the spring. This is likely due to the process of ice melting after a long accumulation of contaminants and washing off activities entering the nearest drains. In autumn, besides Mustoja and Saare Tee, all other basins discharge higher SS than in winter. The summer has less variability while autumn and winter have a high variability in emissions.

Therefore, it is valid for all basins that the spring season is crucial for transporting SS but the same is hard to conclude for other seasons. Summer is more consistence, while autumn and winter are variable for discharging SS. From *Figure 3*, it is clear that half of flows greater than the median values are distributed over a large range. In other words, there is a huge bias towards the upper part. The same result can be noticed in the suspended solid concentration.

Accuracy of Means

The mean of flow and concentration is of great value in estimating total volume and mass emission from the drainage area. *Figure 4* shows a coefficient of variance (CV) for various monitored stormwater parameters for different drainage basins. A CV greater than 1 has a higher variation than mean. Flow, SS, TP and microbiological parameters have greater variation in data than mean, while other parameters have less variability.

Table 4 seeks to determine how much deviation of mean could occur in the analysis of the existing data. Positive and negative CI for mean of flow, conductivity, SS, BOD_7, TN and TP are calculated according to a range from 99% (p-value 0.01) to 70% (p-value 0.3) confidence levels. The mean parameters at 99% confidence interval could vary up or down 18.8 - 161.6% (flow), 26.3 - 56.7% (conductivity), 36.2 - 106.9% (SS), 28.7 - 72.6% (BOD_7), 12.5 - 57.3% (TN) and 27.0 - 64.8% (TN) depending upon the drainage area. Although confidence widths at 70% confidence interval are comparatively narrow, they still vary by plus minus 7.6 - 30.6% (flow), 10.6 - 22.8% (conductivity), and 14.6 - 43.03% (SS) 11.6 - 29.2% (BOD_7), 6.3 - 23.1% (TN) and 10.9 - 26.1% (TP).

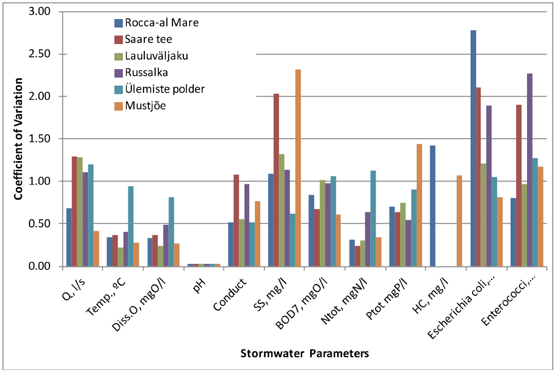

Figure 4: Coefficient of variance of parameters

Table 4: Deviation of mean between two confidence intervals

S. Sit	p-value	Q, l/s		Conductivity, mS/cm		SS, mg/l		BOD7, mgO/l		Ntot, mgN/l		Ptot mgP/l	
		Mean	CI	Mean	CI	Mean	CI	Mean	CI	Mean	CI	Mean	CI
1	(0.01-0.3)	95.84	[(+\-)36.78% to (+\-)14.8%]	818.26	[(+\-)27.12% to (+\-)10.91%]	38.21	[(+\-)57.57% to (+\-)23.17%]	10.56	[(+\-)44.21% to (+\-)17.79%]	4.09	[(+\-)16.44% to (+\-)6.61%]	0.44	[(+\-)37.14% to (+\-)14.94%]
2	(0.01-0.3)	38.42	[(+\-)67.83% to (+\-)27.29%]	1420.52	[(+\-)56.74% to (+\-)22.83%]	22.79	[(+\-)106.94% to (+\-)43.03%]	6.89	[(+\-)37.71% to (+\-)15.17%]	4.61	[(+\-)12.5% to (+\-)5.03%]	0.44	[(+\-)33.6% to (+\-)13.52%]
3	(0.01-0.3)	80.47	[(+\-)75.95% to (+\-)30.56%]	1008.93	[(+\-)28.95% to (+\-)11.65%]	8.43	[(+\-)70.88% to (+\-)28.52%]	8.10	[(+\-)72.55% to (+\-)29.19%]	5.00	[(+\-)16.06% to (+\-)6.46%]	0.23	[(+\-)39.41% to (+\-)15.86%]
4	(0.01-0.3)	150.04	[(+\-)56.25% to (+\-)22.63%]	760.48	[(+\-)50.67% to (+\-)20.39%]	18.26	[(+\-)61.37% to (+\-)24.69%]	9.14	[(+\-)50.69% to (+\-)20.4%]	6.81	[(+\-)32.68% to (+\-)13.15%]	0.13	[(+\-)26.96% to (+\-)10.85%]
5	(0.01-0.3)	115.93	[(+\-)161.63% to (+\-)65.03%]	596.03	[(+\-)26.39% to (+\-)10.62%]	6.19	[(+\-)36.16% to (+\-)14.55%]	7.87	[(+\-)63.16% to (+\-)25.41%]	7.53	[(+\-)57.34% to (+\-)23.07%]	0.10	[(+\-)48.19% to (+\-)19.39%]
6	(0.01-0.3)	184.33	[(+\-)18.81% to (+\-)7.57%]	558.39	[(+\-)33.97% to (+\-)13.67%]	31.97	[(+\-)103.99% to (+\-)41.84%]	5.75	[(+\-)28.71% to (+\-)11.55%]	4.18	[(+\-)15.66% to (+\-)6.3%]	0.26	[(+\-)64.78% to (+\-)26.06%]

There is large uncertainty of mean even when the confidence level is reduced to 70% (*Table 4*). Among them, sampling site 6 (Mustoja) has a relatively narrow deviation of means except for SS and TP. The confidence interval width for concentration narrows as the sample size increased and does not decrease proportionately for more than seven samples (Leecaster et al., 2002). In this case, the sample size is comparatively high (32 samples), but the main influencing factor is the range of data. As in *Figure 4,* it has a large range of measurement, which also illustrates why means of TN have relatively low deviations. In summary, flow and SS have higher uncertainty than conductivity, BOD_7, TN and TP in both confidence levels. There is a significant decrease in confidence width from 90-70% but at 70% confidence level, there is still considerable uncertainty in the mean flow and concentrations.

The above results show the variability in the stormwater data according to the mean value. With such high variability, statistical inferences will be highly uncertain. Therefore, further scrutinisation of sampling method in terms of sampling size and frequency is performed.

Scrutinizing sample size and frequency

Rainfall is categorised based on the size of daily rainfall intensity (DRI). The percentage distribution of rainfall is deemed as small amount of 69%, medium amount of 27% and large amount of 4%. At least 20 samples out of 30 are required for monitoring five years during the snow-free period. To sufficiently address the small, medium and large amount of rainfall, 14, 5 and 1 samples are required, according to percentage distribution of rainfall. During the study period, sites 1 - 5 deficits required number of samples or sample size as shown in *Table 5*. In sampling site 1, nearly 50% small rainfalls are not addressed but it lacks totally the runoff measurements of large DRI. In sampling site 2 and 3, samples are mostly collected when small storms are occurring, but most of the samples in the medium and large daily rainfall are missing. Sampling site 5 has the worst sampling frequency because only some of the medium DRI samples are covered. Finally, sampling sites 4 and 6 are good in terms of sampling for medium and large DRI and also attained relatively better confidence interval. Also, they have relatively good measurements for small DRI. Thus it is noticeable that there is no sufficient sample size and most of flows are captured for small range of DRI (<5mm).

Understanding and quantifying first flush is necessary for predicting environmental impacts on receiving waters and for the efficient design of treatment practices. The first flush wash off usually has the highest concentrations of pollutants, so it is this flush that can prove detrimental to healthy waterbodies. The pollutant loads in runoff after this first flush (over 12 mm of runoff) are assumed to be much smaller and should not have a significant impact on downstream ecology (Davis & McCuen, 2005). As in *Table 5*, the antecedent dry days (at least 7 days) before the runoff starts are counted. The numbers of those days are 12, 6 and 1 with corresponding small, medium and large rainfall during the snow-free period. There is one such sample for each site in snow cover period, which has 0.7 mm of 24 hrs precipitation and has a higher amount of SS, but it is difficult to suggest on the basis of this data how much antecedent dry days and rainfall can affect SS in total. No sample was measured during the snow-free period that can address such antecedent dry days, so it is hard to estimate the contribution of SS due to first flush on total mass emission, and it is difficult to obtain the sample size required to address those SS. It could probably increase the mean concentration and ultimately increase not only the mass emission of suspended solids but also positively related nutrients and pollutants like phosphorus, BOD_7 and microbiological parameters.

Table 5: Categorized rainfall size and approximate number of flow samples corresponding to the rainfall range (negative denotes deficit and positive denotes surplus)

Actual DRI					Approx. samples						Deficit and Surplus						7 days Antecedent dry		
Range, mm	size	no of Rain days	% size of DRI	Reqd no. of sample	1	2	3	4	5	6	1	2	3	4	5	6	no of Rain days	% size of DRI	Sample addressing Antecedent dry days
< 5	Small	417	69%	14	6	12	11	10	0	10	-57%	-13%	-20%	-28%	-100%	-28%	12	3%	NA
5-20	Medium	163	27%	5	8	3	2	6	1	11	48%	-45%	-63%	11%	-82%	103%	6	4%	NA
> 20	Large	23	4%	1	0	0	0	1	0	2	-100%	-100%	-100%	31%	-100%	162%	1	4%	NA

Conclusion

In this study, the monitoring data was analysed to obtain stormwater quality and quantity status in the city of Tallinn. The pollutant concentrations are not very high, compared to surface water quality classes, the stormwater status could be classified as moderate, aside from microbiological parameters. However, it cannot be suggested that the impact from stormwaters are negligible because the maximum concentrations observed were quite high for those basins and the status of the coastal sea is estimated as moderate. The high values of the microbiological parameters refer to possible occurrence of sewage discharges in the stormwater system, except the Ülemiste polder. It is observed that the polder basins function well in minimising the stormwater pollutants, especially in relation to sedimentation.

In more than half basins, positive correlation is found between flow and SS (0.4 - 0.6) as well between SS and TP (0.4 - 0.95).There is significant decrease in confidence width from 99–70% but there is still considerable uncertainty in the mean flow and concentrations at the 70% confidence interval. Flow and SS have higher uncertainty than conductivity, BOD_7, TN and TP at both confidence intervals. The variability in the stormwater is significantly larger than the mean value. Samples to inadequately address the entire rainfall, absence of information for first flush and high variability of data are particular shortcomings of this monitoring programme. Therefore, the stormwater monitoring programme as well the data should be revised in order to use for the further management approaches.

The sampling time during a storm event is quite important in order to prevent variability and improve sample representativeness of grab samples. Meanwhile, flush concentration can also influence substantially in the calculation of mass emission. This sampling time varies with hydrology, impervious surface as well as topology and the basin soil characteristics.

Single storms can be efficiently characterised with small bias and standard error by taking 12 samples with flow proportioned composite samples. The uncertainty of the overall average concentrations becomes reasonably steady as more samples are collected. In all methods, composite samples are taken either to measure total flow or mean concentration for a storm event or both. These composite samples are minimally required to measure flow since it is totally dependent on storm events, thereafter to provide platforms for validation of data.

The rainfall data are fundamental inputs for the analysis of stormwater runoff. Accuracy is achieved when the rainfall station is near to a sampling site. In our study, it is 20 km from Tallinn city centre. It is recommended that installation of a recording rain gauge on site or as close to the sampling site as possible is essential.

Heavy metals are important pollutants from stormwater runoff. These pollutants are detrimental to the waterbodies. Also, salting activity in highway for snow melting provides chlorides ions in the discharges. Proper monitoring of these metals and ions should also be included in the stormwater monitoring programme.

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PAPER II

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TRENDS IN URBAN STORM WATER QUALITY IN TALLINN AND INFLUENCES FROM STORMFLOW AND BASEFLOW

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Abstract. Temporal trends provide a good interpretation of change in stormwater quality over time. This study aimed to analyse trends and influences due to stormflow and baseflow. Grab samples of 18-19 years from 1995 to 2014 recorded at outlets of 7 Tallinn watersheds were analysed for monotonic trend through seasonal Mann Kendall test for long-term, short-term, baseflow and stormflow. Statistically significant downward trends (*P*-value (*p*) < 0.05) were found for 6 – hydrocarbon (HC), 1 – suspended solids (SS), 3 – biological oxygen demand (BOD), 4 – total nitrogen (TN) and 2 – total phosphorus (TP) out of 7 sampling outlets over the last 10 years. Less significant decreasing trends ($p > 0.05$ and < 0.2) for 3 – SS, 1 – BOD, 1 – TN and 1 – TP were identified. Statistically significant long-term upward trends of pH were revealed in 5 basins, which reduced to 2 with 5 less significant upward trends over the 10 year period, indicating improvements in pH reduction. Härjapea has the highest pH without trend but it includes an upward trend of TN at $p = 0.051$. The highly possible causes for downward trends are street sweeping, sewer network improvement, decline in sub-urban agricultural areas, etc. The upward trend results of pH are related to increased alkalinisation due to acidic rain, weathering of carbonate rocks, sewage discharge and alkaline road dust. In most of the basins, stormflow has more influence on trends than baseflow.

Keywords: s*easonal Mann Kendall test, stormwater quality, temporal trend.*

Introduction

Stormwater runoff volume and pollutant load on Baltic Sea is a topic of concern for all Baltic Sea member states. Indeed, HELCOM (Baltic Marine Environment Protection Commission – Helsinki Commission) has made recommendations for restoring the ecological status of the Baltic marine environment. Valid recommendations on the reduction of discharges from urban areas through the proper management of stormwater systems focuses on the volume of runoff and first flush in the separate system and most polluted overflow in the combined system (HELCOM, 2002). One of the major problems in the Baltic Sea region, including Estonia, is eutrophication in water bodies (Iital *et al*., 2010), and urban runoff has contributed substantially in raising nutrient levels (King *et al*., 2007). Significant efforts have been made in the past few decades in reducing the eutrophication of the Baltic Sea. Most recently, the new HELCOM Baltic Sea Action Plan (BSAP) has been adopted by all Baltic countries and by the European Union to reduce the anthropogenic nutrient load and restore the good ecological status of the Baltic Sea by 2021 (HELCOM, 2007). The objectives of the EU Water Framework Directive, HELCOM recommendation and BSAP are reflected in the Estonian Water Act (RTI, 2015b), and it has set a target of protecting all waters against pollution and achieving the good status of all waters by promoting sustainable water and wastewater management. Trends in time series can be one effective interpretation of the increase and decrease in the pollution load discharged from stormwater systems, and this can assist in the decision-making process for further planning with potential drivers for changes in loads.

The regulation of Estonia and HELCOM has set stormwater discharges and pollutant thresholds. It requires compliance verification. According to the Estonian Environmental Monitoring Act, national, local government and special permit owners are responsible for stormwater monitoring (RTI, 2015a). The collection and treatment of wastewater and stormwater are regulated by the Estonian Public Water Supply and Sewerage Act, according to which local government shall develop a plan and activities for stormwater management. Outside the buildings, stormwater and sewerage system are constructed, rehabilitated, maintained and operated according to the Estonian standard EVS 848:2013. The principle is based on returning stormwater to nature either by possible infiltration and delay at sources or reuse. Tallinn has issues with the drainage system in terms of frequent flooding during heavy rainfalls and snowmelts (RTI, 2013b). Instead, the pollution loads from stormwater outlets have a substantial part to play in coastal water degradation, especially in Tallinn Bay (Erm *et al*., 2014) and Kopli Bay (TCG, 2015). The study conducted in 2009 for the ecological status of coastal water in Tallinn city showed moderate ecological status in two of the three studied water bodies of Tallinn Bay (Miiduranna, Pirita) and one in Paljassaare Bay; however, it was bad in one water body of Tallinn Bay (Kalaranna-Russalka) and one of Kopli Bay (Stroomi) (TCG, 2015). Moreover, long-term negative dynamics were observed in these two water bodies. However, long-term improvement trends were found in the Paljassaare and Miiduranna sea areas. The inflow of stormwater is argued as being one potential source for impact on water transparency and depletion of the oxygen level. Thus, the trends of stormwater pollutants are essential for effective understanding of the temporal changed share of pollutant discharges in the ecological status of coastal water. Some of the initiatives introduced in the 2000s by the City of Tallinn have begun to reduce runoff and the pollution load. Many action plans and activities are formulated in the Tallinn Development Plan 2014–2020 (RTI, 2013b), Tallinn Stormwater Strategy to 2030 (RTI, 2012) and Tallinn Water Supply and Sewerage Development Plan 2010–2021, such as reducing the pollution load by street cleaning, minimising hydrocarbon through the installation of oil filters, reducing nutrients building treatment plants, the construction of separate system and the reconstruction of the combined sewer system, etc. The compliance of these initiatives with the reduction of pollutants needs to be ensured over the long-term and short-term periods to make decisions on further planning.

The water moving through the storm drainage system between the rain events, which is called baseflow, has a substantial effect on overall stormwater runoff and quality output (Nicolau *et al*., 2012; Janke *et al*., 2014). Nevertheless, extreme rainfall events have higher impacts on the discharge of pollutants in stormwater runoff (King *et al*., 2007; Erm *et al*., 2014). Research has shown that while phosphorus is predominantly delivered by stormflow, nitrogen loading is similar between the baseflow and stormflow (Janke *et al*., 2014). The temporal changes in pollution require information about the contribution of the illegal connections and / or ground water source and rainfall events. The influences of these flows on overall trends are not yet well defined. Therefore, there is room to investigate how the quality output of baseflow and stormflow influence trends over the years.

The main objective of this study is to discern upward / downward trends of the pollution load in 7 watersheds in Tallinn and to investigate the possible causes behind those trends.

Material and Methods

Study Area

Tallinn, the capital of Estonia, is situated in the northwestern part of Estonia with an area of 156 sq. km. It has a temperate climate where the average air temperature between 1961 and 2010 ranges from -5.9 to -1.0 in January and 12.7 to 21.9 in July (EWS, 2015). The average rainfall is 550–750 mm and the mean runoff is 280–290 mm per year. Most of the land in Tallinn is urbanised, with impervious areas forming about 50% of the total area. There are 66 stormwater outlets (EELIS, 2015). Among them, 47 outlets discharge to the coastal sea. Major outlets that discharge to Tallinn Bay are Härjapea, Saare tee / Pirita, Lasnamäe, Russalka, Ülemiste Polder and to Kopli Bay are Rocca al Mare and Mustoja as shown in Fig. 1. The area of the stormwater system of Tallinn is about 6,500 hectares and the length of stormwater pipeline was 478 km in 2014 (Tallinna Vesi, 2014). Altogether, these 7 outlets approximately cover total area of 4,000 ha.

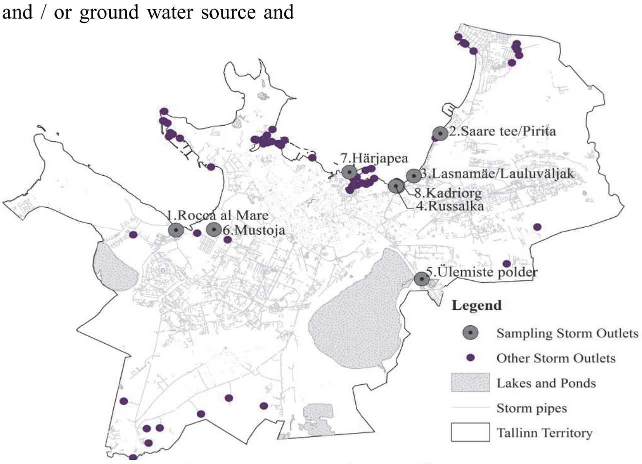

Fig. 1. Stormwater outlets in Tallinn

Data sources and Sampling Strategy

Stormwater monitoring has been carried out since the late 1980s, but it only became regular in the 1990s. For this study, data from three sources have been combined. The first source of data is monitoring reports from Pauklin *et al*. (2005–2011) for the years 2005 and 2008–2011. In this monitoring system, grab samples were collected 4–6 times a year from the stormwater outlets by the Estonian Environmental Research Centre. The data was measured only once in 2010. The second source is monitored data provided by AS Tallinna Vesi, a special water permit owner that has measured samples each month from 1996 to 2014 in 6 outlets: Härjapea, Lasnamäe / Lauluväljak, Pirita / Saare tee, Mustoja, Rocca al Mare and Russalka. Besides these, one other outlet is Kadriorg, which has only two years of data and is excluded for analysis. Six parameters: pH, SS, TN, TP, BOD_7 and HC are measured with grab sampling. The third source is samples measured by both the department of Environmental Engineering of Tallinn University of Technology and AS Tallinna Vesi for the period 2012–2014 in six outlets excluding Härjapea and Kadriorg, but Ülemiste polder is included.

Samples were tested for parameters such as dissolved oxygen, conductivity, pH, temperature, SS, TN, TP, BOD_7, HC, salmonella, Escherichia Coli and Enterococci using analytical methods based on ISO 10523, ISO 5667-10, EVS-EN 25814, EVS-EN 27888, EVS-EN 872, ISO 5815-1, SFS 5505, EVS 9377-2, EVS 9308-1, EVS-EN ISO 7899-2, EVS-EN ISO 6878 and EVS-ISO 6340. All of these are competent bodies according to EN ISO/IEC 17025:2005 for conducting tests in the field of water analysis (accreditation scope on the Estonian Accreditation Centre). The sampling procedure adhered to Estonian Environment Minister Regulation "Sampling methodology" as stated in the Water Act. EVS-EN 25667-2, EVS-EN ISO 5667-3:2012 or any equivalent internationally recognised standard should be followed. These grab samples of 18–19 years from 1995 to 2014 at outlets of 7 watersheds in Tallinn are used for this study. Dissolved oxygen, conductivity, temperature and microbiological parameters have data either less than 10 years or inconsistent. Therefore, these parameters are excluded from data analysis. Since 2012, the records have been available for discharge and sampling times that assist in separating data into baseflow and stormflow. The hourly consistent rainfall data from the Tallinn-Harku Meteorological Station, which is located approximately 20 km from the study area, was obtained from the Estonian Meteorological and Hydrological Institute (EMHI) for 10 years from 2005 to 2014.

Data have been split into baseflow and stormflow by looking at the antecedent rainfall of 3 dry days prior to the sampled time. Most of the dry weather flow samples are taken after a period of at least 3 days without rain (Smoley, 1993, Schiff, 1997; Francey *et al*., 2010) when the runoff does not exceed the minimum sampling threshold. If there is no rain within 3 days or rainfall < 2 mm/hr (also compared with available discharge data) then these data are categorised as baseflow; otherwise, they are stormflow data.

Statistical Methods

Monotonic trends in time series on watershed basis are analysed for six parameters: HC, pH, SS, BOD_7, TN and TP using seasonal Mann Kendall (SMK) trend test (Hirsch, Slack, 1984). Water quality data are usually not normally distributed and exhibit a seasonal pattern (Gilliom, Helsel, 1986). SMK tests are non-parametric tests for the detection of trends in time series. It provides a way for the accounting of ties and missing values and is defined as a sum of all signs of differences in the dataset. The test statistic is called SMK statistics (SMK-stat), which has approximately standard normal distribution according to the central limit theorem. Variance is corrected for ties and serial correlation among seasons during this test (Hirsch, Slack, 1984). The trends are analysed in four kinds of data sets: long-term data set for 18-19 years from 1995 to 2014, short-term data set for 10 years from 2005 to 2014, baseflow and stormflow for the same 10 year period. SMK statistics, 5% and 20% significance levels ($p \leq 0.05$ and $p > 0.05$ to < 0.20) are estimated, the differences between trends are compared and the possible causes are investigated. Significance ranks are provided as 3 for $p \leq 0.05$ indicating statistically significant, 2 for $p > 0.05$ and < 0.20 indicating trends can exist if $p < 0.20$ and no trend for $p > 0.20$ after performing a two-tailed test. The positive and negative sign indicate upward trend and downward trend respectively. There are three factors that drive the performance of the short-term trend test. Firstly, some data do not have 19 years of data but only 10 years, as in the Ülemiste polder. Secondly, consistent hourly rainfall data is only available for this period in order to categorise stormflow and baseflow. And thirdly, the trends observed in the long term may not necessarily appear in the short term or vice versa. Therefore, analysing both long term and short-term data may provide information on these characteristics.

Results and Discussion

The results from SMK test for long-term, short-term, stormflow and base flow are presented in Table 1. This includes SMK statistics, *P*-values and significance ranks. The concentration range of the data from 1995 to 2014 at 7 outlets are presented in Fig. 2 with statistical 10th and 90th percentile, mean, median, maximum and minimum points. The results from Table 1 is summarised in simple form and presented in Table 2 to provide the information of short-term, stormflow and baseflow trends with significance ranks, which make it easier to find the number of statistically significant trends according to basins and parameters. Generally, pollutants concentration and trends show decreasing tendency, thus indicating improved water quality. The results by each parameter are described below.

Hydrocarbons

HC has remarkable decreasing trends in Tallinn because there are statistically significant downward trends in almost all basins, 5 in 7 basins over 19 years and 6 in 7 basins over the 10 year period (Table 1 and Table 2). However, the HC downward trend in Härjapea basin for the long period is less significant (p = 0.076). These downward trends mainly occurred during stormflow, as in Table 1 where 5 out of the 7 basins have decreasing trends at $p < 0.20$, but baseflow has also attributed in some of the basins, e.g. Härjapea, Rocca al Mare, and Russalka. The decreasing tendencies are probably related to either the reduced oil emission from vehicles or trapping oil substances through the installation of oil trappers on the roadsides before entering drainage channels. HC has 90th percentile varied from 2–2.6 mg/l based on catchment basins during the 1995–2014 period (as in Fig. 2). They are less than the stormwater limit value of 5 mg/l, i.e. national permissible concentration of Estonia. However, the annual 90th percentile between 2002 and 2004 exceeded the limit values in the Pirita and Rocca al Mare outlets.

Hydrocarbons can cause problems in receiving water bodies as they can be toxic to aquatic life, depress the oxygen concentration and impart a foul odour. PAH, a compound of HC, even in low concentration can affect aquatic life (Khan *et al*., 2006). The amount of HC in stormwater runoff highly depends on the land use and volume of runoff. In many studies, they are found in higher quantity in highways, car parks, roads and vehicle washing areas than in residential areas (Stenstrom *et al*., 1984, Göbel *et al*., 2007). Dry atmospheric deposition due to the accumulation of dust, aerosol and gas on the roofs and land surfaces form residue and are washed into drainage / waterways as concentrated pollutants during runoff events (Göbel *et al*., 2007). Therefore, street cleaning is highly effective in reducing the HC loads in storm runoff. Indeed, few parking areas and highways in land use can significantly decrease HC concentration. The City of Tallinn has initiated an action plan for implementing street cleaning methods in most of the areas and these practices have been increased in the last few years. Footpaths, roads and car parks are being kept clean and it is made necessary to clean the streets before the spring starts (RTI, 2013b; Tallinna Vesi, 2014). To minimise HCs, they have installed sand and oil filters on stormwater drainage on major roads and car parks (RTI, 2013b). Moreover, local oil separators have been installed around car parks and petrol stations.

Table 1. SMK Test results

Storm outlets	HC, mg/l			SS, mg/l			pH			BOD_7, mgO_2/l			TN, mgN/l			TP, mgP/l		
	SMK Stat	*P*-value	Sig. rank	SMK Stat	*P*-value	Sig. rank	SMK Stat	*P*-value	Sig. rank	SMK Stat	*P*-value	Sig. rank	SMK Stat	*P*-value	Sig. rank	SMK Stat	*P*-value	Sig. rank
18–19 years data (1995–2014)																		
Härjapea	-1.8	0.076	-2	-	-	-	-	-	-	-2.7	0.008	-3	-1.8	0.076	-2	-1.8	0.07	-2
Lasnamäe	-2.3	0.022	-3	-	-	-	**3.2**	**0.001**	**3**	-	-	-	**1.6**	**0.117**	**2**	-	-	-
Mustoja	-3.5	0.001	-3	-1.5	0.122	-2	**3.4**	**0.001**	**3**	-2.8	0.006	-3	-2.8	0.005	-3	-3.4	0.001	-3
Pirita	-2.7	0.007	-3	-2.5	0.012	-3	**3.8**	**0**	**3**	-3.4	0.001	-3	-	-	-	-4.1	0	-3
Rocca-al-Mare	-2.7	0.006	-3	-	-	-	**3.4**	**0.001**	**3**	-3.3	0.001	-3	-	-	-	-	-	-
Ülemiste polder	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Russalka	-2.6	0.009	-3	**1.4**	**0.164**	**2**	**3.5**	**0**	**3**	-	-	-	-2.1	0.032	-3	-2.6	0.009	-3
10 years data (2005–2014)																		
Härjapea	-2.1	0.036	-3	-1.7	0.091	-2	-	-	-	-2.2	0.028	-3	-2.5	0.011	-3	**2.0**	**0.051**	**2**
Lasnamäe	-2.5	0.013	-3	-	-	-	**1.5**	**0.139**	**2**	-	-	-	-	-	-	-	-	-
Mustoja	-2.3	0.021	-3	-1.4	0.154	-2	**1.7**	**0.088**	**2**	-2.3	0.021	-3	-1.9	0.052	-2	-2.3	0.02	-3
Pirita	-2.1	0.034	-3	-1.6	0.12	-2	**2.1**	**0.038**	**3**	-2.1	0.039	-3	-2.3	0.021	-3	-2.3	0.022	-3
Rocca-al-Mare	-3.2	0.001	-3	-2.1	0.037	-3	**1.8**	**0.067**	**2**	-	-	-	-	-	-	-	-	-
Ülemiste polder	-	-	-	-	-	-	**2.7**	**0.008**	**3**	-1.6	0.116	-2	-1.6	0.121	-2	-	-	-
Russalka	-2.7	0.008	-3	-	-	-	**1.5**	**0.13**	**2**	-	-	-	-3.3	0.001	-3	-1.5	0.125	-2
Baseflow																		
Härjapea	-1.6	0.117	-2	-2.0	0.045	-3	-	-	-	-	-	-	-	-	-	**1.7**	**0.089**	**2**
Lasnamäe	-	-	-	-1.6	0.117	-2	-	-	-	-	-	-	-	-	-	-	-	-
Mustoja	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pirita	-	-	-	-	-	-	-	-	-	-1.3	0.197	-2	-	-	-	-	-	-
Rocca-al-Mare	-1.8	0.067	-2	-1.4	0.162	-2	**2.0**	**0.051**	**2**	-	-	-	-	-	-	-	-	-
Ülemiste polder	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Russalka	-1.3	0.183	-2	-	-	-	-	-	-	-	-	-	-1.9	0.064	-2	-	-	-
Stormflow																		
Härjapea	-1.6	0.117	-2	-	-	-	**1.3**	**0.194**	**2**	-	-	-	-	-	-	-	-	-
Lasnamäe	-1.9	0.052	-2	-	-	-	**1.7**	**0.092**	**2**	-	-	-	-2.2	0.026	-3	-	-	-
Mustoja	-1.8	0.069	-2	-	-	-	-	-	-	-1.4	0.166	-2	-2.4	0.014	-3	-2.1	0.038	-3
Pirita	-	-	-	-1.7	0.096	-2	-	-	-	-	-	-	-	-	-	-1.4	0.151	-2
Rocca-al-Mare	-2.4	0.015	-3	-1.4	0.161	-2	-	-	-	**1.9**	**0.056**	**2**	-	-	-	-1.4	0.155	-2
Ülemiste polder	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Russalka	-1.3	0.19	-2	-1.4	0.173	-2	**2.0**	**0.042**	**3**	-1.6	0.114	-2	-1.3	0.19	-2	-	-	-

Table 2. Simplified trends detail with significance ranks

Para-meter	Mustoja			Härjapea			Lasnamäe			Pirita			Rocca-al-Mare			Russalka			Ülemie polder		
	ST	SF	BF	ST	SF	BF	ST	SF	BF	ST	SF	BF	ST	SF	BF	ST	SF	BF	ST	SF	BF
HC	-3	-2	-	-3	-2	-2	-3	-2	-	-3	-	-	-3	-3	-2	-3	-2	-	NA	NA	NA
SS	-2	-	-	-2	-	-3	-	-	-2	-2	-2	-	-3	-2	-2	-	-2	-	-	-	-
pH	+2	-	-	-	+2	-	+2	+2	-	+3	-	-	+2	-	-	+2	+3	-	+3	-	-
BOD	-3	-2	-	-3	-	-	-	-	-	-3	-	-2	-	+2	-	-	-2	-	-2	-	-
TN	-3	-3	-	-3	-	-	-	-3	-	-3	-	-	-	-	-	-	-2	-2	-2	-	-
TP	-3	-3	-	+2	-	+2	-	-	-	-3	-2	-	-	-2	-	-	-	-	-	-	-

ST – short term trend or 10 yr trend, SF – stormflow trend; BF – baseflow trend, -3 – significant downtrend (*P*-value < 0.05) , +3 – significant uptrend (*P*-value < 0.05), -2 – downtrend (*P*-value > 0.05 and < 0.2), +2 – uptrend (*P*-value > 0.05 and < 0.2), NA – data not available.

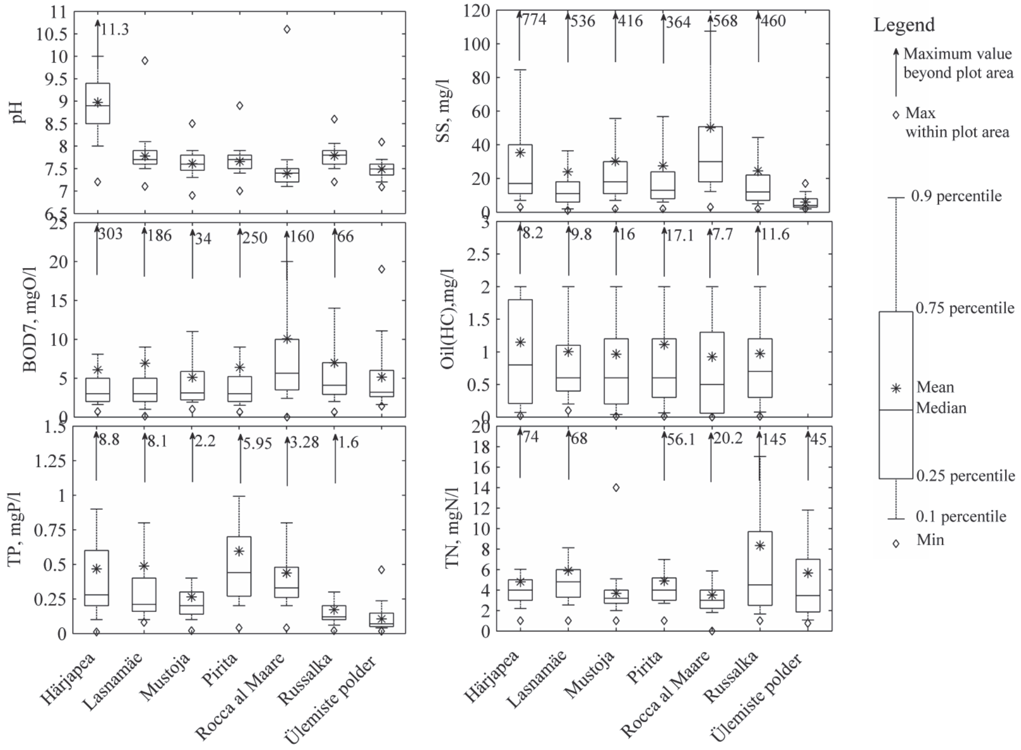

Fig. 2. Concentration range at different stormwater outlets during 1995-2014

Suspended solids

About SS, the number of sites that have decreasing trends doubled from two in 19 year period to four in 10 year period indicating additional reduction in SS. Nevertheless, the levels of significance for this reduction were site specific. One significant long-term downward trend in Pirita outlet (p = 0.012) was found but the P-value has increased resulting less significant decrease in the past 10 years (Table 1). Rocca al Mare has improved in reducing SS since 2005 because it has a significant 10 year downward trend, and both storm and base flow play an equal role in this result (Table 2). Mustoja and Härjapea only show a decreasing trend at P-value 0.15 and 0.09, respectively. On the contrary, Russalka over the long-term reveals a less significant increase (p = 0.164) in SS which does not appear in the short-term, pointing no substantial reduction of SS after 2005. Only in Härjapea is a considerable contribution from baseflow as the result of a decreasing trend (at p = 0.045), whereas stormflow is more influential in Pirita. Overall, SS in Tallinn, though decreasing in 4 sites after 2005, neither have conclusive significant trends nor clear influence from stormflow and baseflow.

Instead, SS in Tallinn stormwater outlets varies a lot. Median and mean of 19 years of SS concentration do not exceed the national stormwater limit value of 40 mg/l in all basins except Rocca al Mare (Fig. 2). Nevertheless, the 90th percentile in most of the basins exceeds the limit, excluding Lasnamäe and Ulemiste Polder. Among them, Härjapea and Rocca al Mare have a large variation. It was noticed that Härjapea in 2001 and Rocca al Mare in 2005 and 2007 have a yearly median value of SS that exceeded the national stormwater limit value of 40 mg/l. The data of SS in all outlets except Ülemiste polder can surpass this limit during heavy rainfalls associated with the first flush and snowmelts in spring.

Suspended solids typically degrade water quality leading to different issues such as aesthetic problems, ecological degradation of aquatic environment, decline in fish resources, higher treatment cost, eutrophication, etc. (Bilotta, Brazier, 2008). They are associated with pollutants such as phosphorus, organic compounds and some heavy metals due to adsorption capacity and can have detrimental effects (Wakida *et al*., 2014). They are comprised of fine particulate matters suspended in storm runoff that have emanated from natural and anthropogenic sources. Natural sources are usually left unregulated because they are naturally present. These sources include forest fires, pollen, mould, etc. Anthropogenic sources are associated with air dust, street dust, salts used for deicing, poorly maintained garden beds / lawns and construction activities. Therefore, one of the most influential controls of SS could be a reduction in the dry atmospheric deposition of air dust, aerosol and gas. In Tallinn, street sweeping has been initiated since a decade ago and it has reduced considerable dry atmospheric deposition. It is evident that the yearly concentration of particulate matters up to 10 µm (PM10) in South Tallinn and the city centre has decreased more than 50% during the 12 years since 2002, though this has decreased nearly 25% during the same period in the Haabersti area (EKK, 2015). This reduction in dry atmospheric deposition has probably revealed significant downward trends in Pirita and Rocca al Mare. Instead, the amount of SS is reduced in stormwater outlets due to renovation and the new construction of storm pipes. The major construction of stormwater pipes occurred in 2005 to 2010 (Tallinna Vesi, 2014). Many discharges from sewerage pipes were diverted to waste water treatment plants (WWTP), reducing the volume of possible WW connection to storm water systems and making storm water cleaner. In wintertime during the snow period, salt is used for de-icing road surfaces. It melts ice but it is also considered the main source for road dust. Chlorides keep damp road surfaces stable and the low temperature water is an enemy for asphalt. There is also more wear of asphalt surfaces if studded tyres are used for vehicles. The wear of the pavement caused by studded tyres is suggested to be ~ 47000 t/y, out of which 5–20% or 2100–10400t/y is the spread into ambient air (Hääl, Sürje, 2006). This characteristic feature probably increases SS concentration in stormwater runoff, particularly during spring.

pH

Noticeably, pH has increasing trends in six out of seven outlets though the trends were less significant after 2005 in most of the basins. However, the pH is in between acceptable range (6–9) in all basins except Härjapea. Statistically significant long-term upward trends at $p < 0.05$ for pH are obtained in 5 out of 7 sites: Lasnamäe, Mustoja, Pirita, Rocca al Mare and Russalka, but except Pirita, P-values increased during last decade resulting less significant trends (Table 1). Ülemiste Polder has pH data from 2005 and SMK test for this period reveals significant upward trend. Stormflow is more influential for pH increase (3 out of 7 sites) than baseflow (1 out of 7 sites) (see Table 2). Only in Rocca al Mare, baseflow with upward trend at $p = 0.051$ is effective to attribute increased pH. In the stormwater outlets, the average pH over 19 years varied from 7.4–7.8 except in Härjapea where it has the highest level at 9 (Fig. 2). Moreover, 90th percentile pH ranged 7.8–10 with the highest in Härjapea.

Measurement of pH indicates acidity, basicity, alkalinity and neutrality in terms of hydrogen ions concentration in solution. The most preferable range of pH for the aquatic organisms is from 6.5 to 8, though the US EPA suggests 6.5 to 9 in freshwater as water quality criteria. The lower and higher ends of this range affected many species in terms of reproduction, growth and diseases (Ohrel *et al.*, 2006). In Estonia, the pH of discharged water to the coastal area should be between 6 and 9 (RTI, 2013a).

A high pH has direct and indirect effects on aquatic life. As a direct effect, prolonged exposure to pH > 9.5 can damage outer surfaces such as fish gills, skin and eyes. It can also harm fish olfactory system, reducing detection capability for food, sex hormones and toxic chemicals. As an indirect effect, it has the proximity of ammonia toxicity. Since the fraction of unionised ammonia is more than 100 times greater than ionised ammonia when the pH is higher, toxicity exposure is increased during daylight hours.

The illustration for the increasing trend of pH in the respective sites is difficult to explain because there are different sources that can cause an elevated pH level. The main contributing factors in Tallinn that can be argued are storm drains from carbonate lithology, roads and impervious surfaces and sewage discharges that are primarily from industrial areas. The first contributing factor can be illustrated by increased alkalinisation and acid deposition (Kaushal *et al.*, 2013). Inorganic carbon fluxes increase due to development in urbanisation, changes in agricultural liming and mining, which contribute to bicarbonate alkalinity in rivers and streams. Another influential factor for increased alkalinity can be related to acid rain and the weathering of carbonates in bedrock, soils and cement (Kaushal *et al.*, 2013, Barnes, Raymond, 2009). It is because the weathering reactions produce alkalinity during acid neutralisation by geological materials. The rainfall data in Tallinn for the past 19 years indicate that the pH trend has been significantly decreasing as in the SMK test result shown in Table 3. It is evident that precipitation in Tallinn is becoming more acidic. The Tallinn region is in the north-western Estonia, which belongs to Quaternary cover of a depth of 5 to 10 m. Sandy and clayey soils occur in the seashore area. Cambrian claystone, sandstone and siltstone are bedrocks in most of the basins, but the western area of Tallinn has Ordovician carbonate rocks such as Lasnamäe, Ülemiste and Russalka. The composition of these underlying rocks determines the major lithogenic element distribution of soils (Reintam *et al.*, 1999). The high abundance of clay minerals and iron oxides are prevalent whereas oxides of Al, K, Ca and Mg are also enriched with clay minerals. Carbonate rocks from surrounding quarries have been used for limestone and dolostone for hundreds of years in Tallinn. Old churches, stone walls and building walls have been constructed with these rocks (Bityukova, 2006). Huge amounts of carbonate rocks have been mined and used for road construction material such as aggregates, gravels, fillers in asphalt and white road-marking mixture, for cement producing and for agriculture and garden liming (Notton, Sõstra, 2010). The decay of these carbonate rocks can occur due to weathering from the acidity of rainfall and, as a consequence, alkalization with pH can increase in the runoff.

The volume of traffic has also increased in this region, which damages the road surfaces, particularly in winter when studded tyres are used and de-icing salts is applied. This accelerates the weathering of road surfaces.

When the volume of traffic is increased, it influences air pollution because the concentrations of NO_2, SO_2, CO and PM10 are highest during working hours. The road areas produces alkaline dust, which can increase the pH found in tree bark in the range from acidic to subneutral, and this dust is highest in the centre of Tallinn (Kesklinn) rather than suburbs such as Rahu (an industrial area) and Õismae (a residential area) (Marmor, Randlane, 2007). In addition, sewage discharge contains carbonate compounds because the industrial process involved in making fertilisers, plastics, ceramics, rubber, paint, glass, glass fibre and sugar uses carbonate rocks. Also, the discharge of soap and detergents most likely increases the alkalinity in water considerably.

In Härjapea, the yearly 90th percentile of pH ranged 8.4–10.8 and yearly mean ranged 8.1–9.78 over 18 years, which is the highest average pH of all basins; however, there is no significant trend observed in this outlet. From 1996 to 2002, the annual pH level increased to a maximum of 9.78, and it began to decline from 2003 onwards. The decline is not as steady as in 2007 when there was a high pH of 9.58 and in 2013, it reached 8.87. This region includes the areas of Põhjaväila and the streets of Lootsi and Ahtri along with suburbs of the central city. The Old Town with its historic buildings, medieval stonewalls, churches, stone pavements and old houses have the option of partial discharge to this outlet. On the one hand, there is a significant possibility of weathering of the carbonate rocks in these areas. On the other hand, due to the increased traffic volume, dust pollution has increased in the city area; for example, in 2006, the 24h limit value of 50 $\mu g/m^3$ was exceeded on 42 occasions in the Kesklinn area (Marmor, Randlane, 2007). Moreover, the factories and old sewerage system have the potential to discharge sewage containing carbonate compounds. In recent decades, the city government has made many efforts to protect and improve the Old Town environment in Tallinn. Roads were reconstructed, traffic was limited, some small enterprises were removed to the outlying areas, etc. (Bityukova, 2006). This is a probable explanation for the increases and decreases during this period.

Biological Oxygen Demand (BOD)

BOD concentration, that seldom exceeded the permissible value, has remarkable decreasing trend in nearly half of the studied outlets. Within the period of 19 years, the 90th percentile of BOD concentrations are below the stormwater national limit value (15 mg/l), excluding Rocca al Mare which reached 19 mg/l (Fig. 2). Mustoja and Rocca al Mare exceeded this limit value in the years before 1997, but since then the yearly median values have been within this limit. Statistically significant downward trends have been noted for BOD_7 in 3 basins: Härjapea, Mustoja and Pirita (Table 1). Pirita's downward trend is associated with baseflow (p = 0.197) and Mustoja's with stormflow (p = 0.166), while Härjapea does not show trends in stormflow and baseflow. Rocca al Mare has significantly decreased BOD in the 19 year period but it has not shown a trend in the past 10 years. This characteristic feature can be associated with an increasing trend in the stormflow at p = 0.056 (as in Table 1) because the trend for stormflow reveals that during this period only storm events caused a rise in BOD concentration levels against the long term decreasing trend.

Naturally, fallen leaves and decaying vegetation increase the oxygen demand in runoff. In addition, anthropogenic activities such as grass clippings, human, birds and animal excreta, hydrocarbons, engine coolants and antifreeze containing ethylene glycol and propylene glycol can exert high BOD in stormwater (Bingham, 1993, Erickson *et al.*, 2013). BOD in urban runoff can be directly correlated with watershed development and percentage impervious surfaces (Erickson *et al.*, 2013). Göbel *et al* (2007) found in many research works that BOD is higher in runoff in traffic areas than in runoff from gardens, lawns and cultivated areas. However, a significant load originates from roofs due to bird excretion and dry atmospheric deposition. In Tallinn, a significant decrease in BOD is mainly observed in three watersheds, such as Härjapea, Mustoja and Pirita. According to the environmental reports of AS Tallinna Vesi (Tallinna Vesi, 2014), sewerage networks were constructed at Mustamäe (region of Mustoja watershed), Pirita and the city centre (regions of Härjapea watershed). In 2004, the sewerage connections for the residential area of Lilleküla and also catering for the Tondi area were constructed under Mustamäe road. In the districts of Merivälja, Lilleküla and Mustamäe, some streets were directly linked to combined sewers leading to WWTP in 2005. This has considerably reduced BOD and other organic pollutants in those areas. The large volume of sewerage extension occurred between 2005 and 2010. Moreover, the municipalities initiated street sweeping, which has remarkably prevented organic matters from mixing with runoff. The Pirita district has mainly improved the sewerage connections to reduce the pollutant load in the outlet. However, in Rocca al Mare, BOD concentration is not well controlled and it showed increasing volumes during storm events, indicating possible wash-off of animal waste from upstream Tallinn Zoo.

Nutrients

In the case of nutrients, the results reveal nearly half of the basins have decreasing trends and two basins considerably improved TN reduction over the last 10 years. From 2005 to 2014, 4 statistically significant downward trends of TN (at Mustoja with $p \sim 0.05$, Härjapea, Pirita and Russalka) and 2 statistically significant downtrends of TP (at Mustoja and Pirita) have been observed (Table 1 and Table 2). However, the TN trend for the long-term period in Pirita does not appear and in Härjapea it is less significant. It indicates that there have been considerable reduction activities for N in these two basins since 2005. On the contrary, Lasnamäe's long-term trend is less significant but does not appear to be a short-term trend, suggesting no considerable improvements in N concentration after 2005. Nevertheless, it is interesting to know that Härjapea has begun to see a rise in TP for the past 10 years and baseflow (at p = 0.089) is mainly contributing to this result. In most cases, the decreasing trend in nutrients is formed during stormflow.

Nutrients' 90th percentile concentrations, at 5.1–16.9 mg/l of TN and 0.2–1 mg/l of TP, do not exceed the stormwater limit value. However, the concentrations are over levels causing eutrophication (Fig. 2). The mean TN and TP in the inlet of WWTP Tallinn in the last 10 years were 44.6 and 6.8 mg/l respectively (Tallinna Vesi, 2004-2014), whereas stormwater runoff TN and TP in stormwater outlets have varied between 3.5–8.4 mg/l and 0.1–0.6 mg/l respectively, as in Fig. 2. According to Estonian regulations, the stormwater limit values of TN and TP are 45mg/l and 1 mg/l (RTI, 2013a) which is far higher than coastal water class 5 limit values (0.97 mg/l of TN and 0.67 mg/l of TP) and river water limit values (6mg/l of TN). Sometimes, the concentrations during heavy rainfall with first flushes almost reached the mean concentrations of inlet WW with yearly 90th percentile of 36.9 mg/l (TN) and 4.8 mg/l (TP). Some years, the areas of Härjapea and Pirita reached the stormwater TP limit value (1 mg/l), resulting in the 90th percentile of 0.9 mg/l and 1 mg/l, respectively. Similar to river and streams, natural and anthropogenic sources contribute to nutrients in stormwater runoff. Natural sources for nutrients in the urban area include ground water, atmospheric nitrogen and vegetation, e.g. some N-fixing plants. Natural biochemical processes during the decomposition of plant and animals can occur in the watershed to contribute to nutrients.

Table 3. SMK-test results for trends analysis of air quality and precipitation in Tallinn (Statistics Estonia, 2015, EEA, 2015).

Parameters	Period	Annual average range	SMK Stat	*P*-Value	Sig. rank
Tallinn Air Quality Monitoring					
SO_2, µg/m³	1995 to 2014	1.1–8.0	-4.546	<0.001	-3
NO_2, µg/m³	1995 to 2014	14.4–101.6	-4.385	<0.001	-3
CO, mg/m³	1995 to 2014	0.2–1.7	-5.086	<0.001	-3
PM, µg/m³	2006 to 2014	12.3–29.5	-2.488	0.013	-3
Tallinn Precipitation Pollutants					
pH	1995 to 2014	5.6–7.4	-3.943	<0.001	-3
SO_4-S, mg/l	1995 to 2014	0.4–9.6	-4.207	<0.001	-3
NO_3-N, mg/l	1995 to 2014	0.2–1.1	1.693	0.091	2
Cl, mg/l	1995 to 2014	0.7–4.2	-0.905	0.365	-1
NH_4-N, mg/l	1995 to 2014	0.1–0.6	1.111	0.267	1
Precipitation, mm	1995 to 2014	39.2–78.0	0.062	0.951	1
HCO_3,mg-ekv/l	2003 to 2014	0.1–56.4	-2.09	0.037	-3

Overflows from sewer systems and the leaching of sewerage due to poor drainage systems can be expected in some areas of Tallinn. This century, there has been extensive stormwater and sewerage network construction and renovation in Tallinn, which has lasted almost a decade (Fig. 3). According to environmental reports from AS Tallinna Vesi (Tallinna Vesi, 2014), 97% of Tallinn area was connected to the public sewerage system by 2006 and, in collaboration with the City of Tallinn, the company had covered 99% with the public sewerage network by the end of 2010.

In the urban environment, dissolved inorganic nitrogen (NOx-N and NH_4-N) is emitted from vehicle exhausts and the combustion of fossil fuels such as coal and oil. These emissions are accumulated as wet and dry deposition in the atmosphere. Wet forms are rain, snow, fog and hail, while dry forms are particulates, gases and droplets. They are either infiltrated into the soil or washed off into the drainage system. The air quality monitoring records of Tallinn as in Table 3 show that there is a significant decrease in the dry deposition of nitrogen dioxide in the atmosphere. However, the wet deposition does not show the same behaviour because there has not been a significant decrease or increase trend for NO_3-N and NH_4-N in precipitation in the past 19 years (see Table 3). Instead, the nitrogen compound has tended to increase during this period (Table 3). The wet deposition source of dissolved nitrogen is comparatively small in quantity, which cannot contribute to the nitrogen level in stormwater runoff. Similarly, wet deposition in the precipitation of dissolved phosphorus is negligible at the median concentration of 0.005 mg/l during the record period from 1995 to 2002 (EEA, 2015). The atmospheric deposition varies with land use patterns and the volume of emissions. It is not valid in every area of Tallinn and the nitrogen load is high where the number of vehicles and impervious surfaces is significant (Hou *et al.*, 2012, Shen *et al.*, 2014).

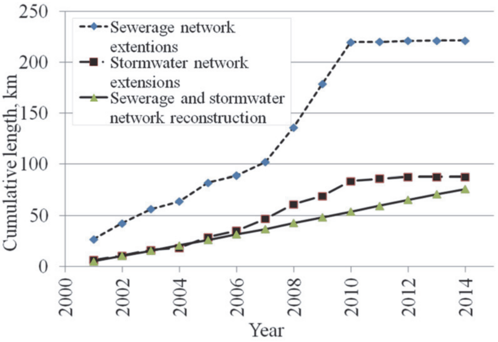

Fig. 3. Cumulative stormwater and sewerage network extension and reconstruction in Tallinn. (Tallinna Vesi, 2014)

Another potential source for stormwater runoff nutrients can be related to fertiliser application in lawns and gardens. Runoff drainage from agricultural and residential lands has much higher nutrient yields than runoff drainage from forested land (Roberts, Kolosseus, 2011), especially during storm events. Lawns and gardens are larger contributors of N and P than streets. Indeed, streets supply particulate nutrients because they are large source of suspended solids (Waschbusch *et al.*, 1993). In agriculture, there is a lowered application of organic and inorganic fertilisers in Estonia (Iital *et al.*, 2010). Instead, the utilisation of organic fertiliser has reduced while usage of inorganic fertiliser has increased (Statistics Estonia, 2015). The constituents that nitrate from them are readily soluble and can be reduced through denitrification. It is one of the likely reasons why the trends of nutrients in Ulemiste Polder and in Russalka have decreased. The upstream basin of the Ülemiste polder sites has agriculture fields and the overflows during heavy rainfall and snowmelt are diverted to the Russalka outlet. Both the Mustoja and Pirita basins have private yards covering approximately 18% of the basin area where the roof runoff as well as rainfall water flows over the yards, with some infiltrating and the remainder flowing into drainage inlets.

There are other possible anthropogenic activities for the diffuse sources of nutrients in stormwater runoff. Rainfall is more concentrated with nutrients once it flows through the surfaces e.g. roofs where there are organic pollutants like leaves, animal or bird excreta, flowers and pollen (Göbel *et al.*, 2007). Vegetation in drains and ditches enhances decay and the decomposition of organic compounds to increase nutrients.

Stormflow is more susceptible to a decrease in nutrient trends than base flow, as shown in Table 2. Compared to the past, the overflow frequencies and volume that divert to storm pipes during storm events are less in quantity, and the reconstruction and construction of sewer pipes have been mainly attributed to this result. It is likely to be a reason that significantly enhances or considerably decreases the volume of nutrients. However, the nutrient concentration in Tallinn stormwater requires study due to the unusual exceeding of limit values, and further investigation can be directed towards determining such patterns.

Conclusion

Downward trends for HC were detected; 6 out of 7 investigated basins have statistically significant downward trends over the past 10 years. The possible reason is street sweeping to keep the roads and parking areas clean and sand and oil trappers on the drainage inlets, which prevent HC from entering the drainage pipes.

SS downward trends are observed in 4 sites but statistically significant downward trends include one in Rocca al Mare for the past 10 years and one in Pirita for the last 19 years. Reduced particulate matter in the air, the connection of WW to sewerage pipes and reduced salt de-icing practice have probably reduced SS in stormwater.

Increased pH trends in most of the basins, except Härjapea have likely been caused by increased alkalinisation due to acidic precipitation, the weathering of carbonate aggregates, discharges and alkaline dust from roads. However, Härjapea stormwater outlet has shown the highest average pH level at 9. One potential reason might be sewage discharge and requires further investigation.

Statistically significant decreasing trends for BOD of three outlets (Pirita, Härjapea and Mustoja), TN of four outlets (same as of BOD and Russalka) and TP of two outlets (Pirita and Mustoja) were observed from 7 outlets over the last 10 year period. Two stormwater outlets, Mustoja and Pirita have shown significant decrease for BOD, TN and TP. The improvement in sewer networks, street sweeping, the decline in the use of agricultural land, and in turn fertilisers have favourably influenced the result.

In general, most of the studied parameters are in decreasing trends except pH which requires more attention to ensure the potential causes and most of the basins' trends have been influenced by stormflow rather than baseflow. Stormflow has a greater influence on HC, SS, pH, BOD, TN and TP trends than baseflow.

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PAPER III

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Towards effective monitoring of urban stormwater for better design and management

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Abstract. The lack of information due to insufficient data availability and an improper sampling method for stormwater generates constraint and uncertainty in addressing all storm events. In such conditions, it is difficult to assess actual concentrations and mass loads. This results in a backlog in decision-making for sustainable planning, design and policy formulation, e.g. retrofitting alternatives to traditional systems for reducing runoff and pollutants. It is essential to set standardized sampling and analysis procedures in order to achieve reliable and representative data. They need to be optimal and effective due to the costs and difficulties in sampling and analysis. The study reviews the effectiveness of largely best practiced sampling procedures in research papers. Likely site selection approaches, monitoring parameters and sample collection systems are compiled with their effectiveness, affordability and applicability. An optimal stormwater sampling programme is deducted and recommended for Tallinn stormwater catchment area. Moreover, the study provides an opportunity to select the suitable monitoring programme from the effective options such that it can be utilized to obtain coherent stormwater data.

Key words: stormwater monitoring, sample collection system, sampling programme, mass loads.

Abbreviations:

ADV – acoustic Doppler velocity
BOD – biological oxygen demand
CHIAT – Chemical Hazard Identification and Assessment Tool
COD – chemical oxygen demand
DEHP – di(2-ethylhexyl) phthalate
DO – dissolved oxygen
DOC – dissolved organic carbon
DTN – dissolved total nitrogen
EC – electrical conductivity
EMC – event mean concentration
MOH – mineral oil hydrocarbon
NA – not available
PAH – polycyclic aromatic hydrocarbon
PCB – polychlorinated biphenyl
PP – priority pollutant
SMC – site mean concentration
SS – suspended solids
TDS – total dissolved solids
TKN – total Kjeldahl nitrogen
TN – total nitrogen
TOC – total organic carbon
TP – total phosphorus
TS – total solids
TSS – total suspended solids
TTU – turbidity
USGS – US Geological Survey
WFD – Water Framework Directive
XOC – xenobiotic organic compound
γ-BHC – gamma-benzene hexachloride

INTRODUCTION

There are potential drivers that augment stormwater monitoring in different countries. The US National Pollutant Discharge Elimination System permit programme has regulated point source pollution from urban stormwater, industrial discharges and construction activities [1–3]. In Europe, the Water Framework Directive (WFD) [4] has endeavoured to protect and improve aquatic ecosystems by reducing the emissions of various pollutants, including those from point and diffuse urban pollution sources. In Estonia, in order to prevent and minimize stormwater runoff volumes and the pollution load, the Baltic Sea member states jointly pooled their efforts through the Helsinki Commission towards the ecological restoration of the Baltic Sea [5]. Furthermore, the European WFD as well as the Estonian Water Act [6] have set a target to protect all waters against pollution and to achieve the good status of all waters by promoting sustainable water and wastewater management [7].

Since stormwater contaminants are discharged from a large number of individual points over a wide range within the catchment, their characteristics and contaminant loadings are not easily understandable [8]. Runoff in stormwater is intermittent, as it depends on the magnitude of rainfall, land use and anthropological activities in the catchment area. Insufficient data availability and an improper sampling method produce constraint and uncertainty that can characterize storm events. Meanwhile, it is difficult to assess annual average and event mean concentration (EMC) and this causes troubles in decision-making for sustainable planning, design and policy formulation [9,10]. Representative data are the ultimate requirement for quality assessment. Obtaining them encounters many barriers and difficulties such as (i) the numerous monitoring locations, which may require intensive sampling and high efforts, (ii) the spatial and temporal variability of parameters and concentrations and (iii) the constraints in the budget and applicability of sampling methods. These barriers will increase the uncertainties in achieving reliable and representative data. Therefore, it is important to set standardized sampling and analysis procedures that need to be optimal and effective for that purpose [1].

Numerous guidelines and procedures have been proposed in documents for stormwater monitoring (ANZECC & ARMCANZ [11], US EPA [12], Geosyntec Consultants and Wright Water Engineers [13], etc.). Many guidelines have not been designed precisely with a deductive consideration of the objectives and sampling requirements [14,15]. In addition, the required level of uncertainty is often unclear; therefore, the appropriate frequency and timing of sampling is not well understood [15–17]. There are practical guidelines that have been illustrated for automatic sampling [18,19], which are not always feasible and/or affordable. In previous research rarely any attention has been paid to approaches for the appropriate site selection, selecting minimum parameters and choosing options based on the degree of the required certainty and cost.

The typical monitoring methods for discharge, sediment and water quality data have been classified into four categories: discharge measurement, sample collection, sample preservation/storage and laboratory analysis. Uncertainties in the sources of these methods contribute to uncertainty regarding the final estimated concentration or load of interest [20–22]. Discharge measurement and sample collection comprise a significant percentage of total uncertainty, i.e. 7–23% for discharge measurement and 14–36% for sample collection [21]. Therefore it is possible to reduce significant uncertainty of the final value by minimizing individual sources of uncertainties through a proper sampling strategy.

In Estonia, environmental monitoring is carried out on three different levels according to the Estonian Environmental Monitoring Act [23]. They are (1) national monitoring for a long-term programme undertaken under sectors including the Estonian Environmental Agency, Estonian Environmental Board and national institutions, (2) local government monitoring by local authorities and (3) the monitoring by an undertaking body for the area affected by its activities or by discharged pollutants. The regional department of the Environmental Board under the Ministry of Environment issues special water permits to water users. According to the special water permit, water users or the owner of this permit should ensure the monitoring of wastewater and stormwater volumes as well as pollution parameter concentrations based on the locations and frequency specified by the permit. The permit issued by regional Environmental Boards establishes the rights and obligations for water users, including security measures and monitoring responsibilities related to water use. The Environmental Board is responsible for the organization and verification of the compliance of monitoring activities. The local government provides a procedure for implementing the environmental monitoring programme and for processing and storing environmental monitoring data. Several research projects investigate stormwater quantity and quality, but all the studies give only a general picture of stormwater. It has been emphasized as an important activity to develop a stormwater monitoring programme in the Tallinn Development Plan 2014–2020 (Tallinn City Council Regulation No. 29, 13/06/2013) [24] and Tallinn Stormwater Strategy until 2030 (Tallinn City Council Regulation No. 18, 19/06/2012) [25]. Therefore, an effective and affordable monitoring programme is the first essential step towards stormwater management in Estonia.

The main objective of this research is to review the existing papers in the monitoring programme for the sample collection system and discharge measurement, such that an optimal and effective monitoring programme could be assessed and a sampling programme recommended for the Tallinn watershed. The paper provides the options for choosing an appropriate sampling programme that could balance the degree of certainty and resource availability. Overall, it ensures proper guidance and recommendations for all planners and designers to design the monitoring programme.

METHODOLOGICAL CONSIDERATION

The study is based on the literature reviews of relevant published papers, robust monitoring programmes, protocols and guidelines. The important aspects of a monitoring programme are the selection of monitoring locations, selection of sampling parameters, discharge measurement and the sample collection system that includes the sampling mode, frequency and storm numbers. Different methods, criteria and uncertainties from previous researches related to these aspects are studied. Effective and recommended methods are assessed so that the selection of methods for monitoring can be made according to the required criteria and certainty. In most cases, the cost of sampling methods is proportional to the increase in certainty but the constraint in the budget often intervenes to applying a more advanced method. Thus, the information about the options of methods with relative uncertainties will be helpful to pick the one that balances the budget and quality output. This information is applied to form an optimal and effective monitoring programme that is also applicable to the Tallinn watershed for which the local criteria and budget constraint are considered.

Selecting monitoring locations

Monitoring additional sites affects monitoring resources because it increases the cost of sampling and analysis. Due to budget constraints, it is not possible to sample all stormwater outlets in an area. Moreover, the stormwater quality characteristics vary significantly between sampling locations and events [26]. Therefore, there are challenges in reducing the variability of quality data, and confusion on whether to choose between sampling more locations with less detailed monitoring or sampling a limited number of locations with detailed monitoring [27,28].

The selection of monitoring locations has received little attention in the literature of stormwater monitoring. Runoff quality data can be transferred to the unmonitored sites while estimating the pollution load according to Marsalek [29]. Lee et al. [27] recommended selecting a subset (~10%) of each monitored category using the advanced sampling method (especially, composite samplers) and using grab samples for the remainder. It is a reasonable approach that may result in a lower overall cost with improved accuracy and variability. Meanwhile, Langeveld et al. [28] proposed collecting metadata during a quick scan through grab samples for all selected locations after pre-screening and screening so that a system dynamic would be determined and there would be less chance of monitoring failure at those locations. They selected three out of 700 storm sewer outfalls. The methodology they proposed and the criteria for each step during selection are summarized in Table 1.

The criteria included in pre-screening and screening are commonly considered in USGS guidelines, Caltrans, New Zealand, stormwater guidelines, etc. for characterizing the monitoring sites [19,30]. However, the quick scan method is rarely applied. This method reveals the dynamic response of the monitoring sites and minimizes substantially the probability of failure of the research or monitoring projects. Additionally, the parameters that exist in a negligible amount and do not have any impact on health and aquatic life can be discarded. This enhances not only the selection of appropriate monitoring locations, but also the subsequent detailed design of the monitoring equipment and sampling strategy. Though certain investment is necessary, it is a relatively inexpensive procedure because the dataset can be gathered using a very simple and relatively cheap (~10% of the overall research budget) approach [28].

Table 1. Methodology for selection of locations [28]

Steps	Criteria	Criteria details
Pre-screening	a) General suitability	Connected impervious area, outfall location, hydraulic structure, backwater effect, etc.
	b) Representativeness	Catchment characteristics (residential/non-residential), construction period, population density, average income, type of road (high/low traffic density)
Screening	a) Personnel Safety	Traffic conditions and criminality
	b) Equipment security	Vandalism (need to house within secure cabinets/ sheds or not)
	c) Site accessibility	Travel distance
	d) Available space	For monitoring equipments, flow measurement capability
Quick scan	a) Metadata on water quality	Data collected through grab sampling (min. 3 events)
	b) Data on system dynamics	Data collected through the methods, e.g. installing surrogate water quality sensors or using water level sensors, sample using batches, etc.
Final selection	a) Representativeness	Details as in pre-screening
	b) Rank	Based on expert judgment

Selection of parameters

A broad range of contaminant profiles has been reported in previous studies about common pollutants and sources around the world [3], and large variations may even be found in a single catchment [2]. Potential influential factors for this variation are rainfall and catchment characteristics [31–33]. Due to this variation, it is difficult to predict stormwater quality characteristics, though it is highly important and feasible to get as much information as possible. One way of approaching this is to point out the few but most important parameters that will ensure broad-spectrum testing and comparable datasets [1]. This would also provide guidance to avoid potentially unnecessary parameters and thereby lower the costs of monitoring.

Potential stormwater quality parameters

Urban stormwater runoff is comprised of various substances with different hazard potential. A summary of the possible contaminants during the three decades of scientific research into stormwater is presented in tabular form by Makepeace et al. [34]. The most critical stormwater contaminants affecting humans, with respect to drinking water and the aquatic life, are presented in Table 2 with reference 'A'. Göbel et al. [3] compiled an intensive literature search for about 1300 data from 300 papers (1982–2004) on the distribution and concentration of surface-dependent runoff. They revealed that macropollutants consisting of major ions with high concentrations and trace elements with low concentrations may possess high hazard potential. Primarily, 22 pollutants have been observed from 12 different drainage surfaces in those publications, which are referenced as 'B' in Table 2. Similarly, the European WFD (2000/60/EC) defines a primary objective for member states in achieving a good ecological and chemical state in surface and groundwater bodies [7], and it sets rigorous water quality standards for priority pollutants (PPs). A list of 33 priority substances was thus regulated as part of Decision No. 2455/2001/EC issued by the European Parliament and Council.

Eriksson et al. [35] proposed a scientifically justifiable list of selected stormwater PPs to be used, e.g. for the evaluation of the chemical risks occurring in different handling strategies using the adapted version of the Chemical Hazard Identification and Assessment Tool (CHIAT) methodology. The list consists of 25 pollutants referenced as 'C' in Table 2 including eight of the PPs (Cd, Ni, Pb, polycyclic aromatic hydrocarbons (PAHs; naphthalene and benzo[a]pyrene) and di(2-ethylhexyl) phthalate (DEHP), nonylphenol, pentachlorophenol) currently identified in WFD. Nevertheless, not all pollutants were addressed for urban stormwater quality [36,37] and, thereby, Zgheib et al. [37] established an intensive list of 88 substances as PPs (i.e. 65 organic substances, 8 metals and 15 volatile organic compounds), based on the WFD list of priority substances and CHIAT. However, these pollutants are different for combined and separate sewer systems. In 2011/2012, based on the theoretical assessment of PPs and CHIAT, 55 PPs were detected in separate stormwater [38], while in a combined sewer 49 PPs (19 were priority hazardous substances) were detected in the runoff from Paris and its suburbs [36]. Separate and combined sewers have common pollutants (reference 'D' in Table 2) such as pesticides, metals (Zn, Cu, Pb), DEHP, PAH, polychlorinated biphenyls (PCBs) and organotin or tributyltin compounds, but higher hydrophobic organic pollutants and some particulate-bound metals in combined sewers. A major risk from PAHs, tributyltin compounds and chloro-alkanes persists in the combined system in relation to the environmental quality standard, whereas metals, PAHs and PCBs are potential risk substances in stormwater. Ingvertsen et al. [1] reviewed and categorized contaminants taxonomically into five groups: suspended solids (SS), heavy metals (Zn and Cu), xenobiotic organic compounds (XOCs) (phenanthrene, fluoranthene and benzo(b,k)fluoranthene), nutrients (N and P) and pathogens. Indicator pathogens and other specific contaminants (i.e. chromium, pesticides, phenols) should be included if recreational or certain catchment-scale objectives are to be met. They proposed a minimum data set of eight key contaminants (reference 'E' in Table 2) to provide a reliable and comparable measure of treatment efficiency.

In addition, physicochemical properties (reference 'F') are essential in order to obtain information on the concentration, stability, bioavailability, etc. of elements and compounds in natural processes and materials, or technical operations and products [39]. The characterization of the initial physicochemical state of the sample is a pre-condition of all further sample preparation steps because it influences the parameter concentration. Often, these properties vary greatly in time and space. The exact values, or rather mean/median values, of the concentration of elements and compounds, can serve as key parameters in exposure and risk assessment. Unless the variations in critical properties of matrices are not taken into account, they will not be meaningful and usable. Several parameters (e.g. pH, temperature and dissolved oxygen (DO)) cannot be analysed adequately after transport to the laboratory

Table 2. General stormwater monitoring parameters including selected priority pollutants. NA, not analysed

Parameter	Unit	Range	Stormwater problem		
			Human	Aquatic	Reference
Physicochemical parameters					
pH	–	3.9–7.9	Minor	Minor	ABCF
EC	µS/cm	25–2436			BF
Temperature, colour, TTU, TOC, DOC					F
BOD5; COD	mg/L	2–36; 55–146	Minor	Minor	B
DO; total solids	mg/L	0–14.0; 76–36, 200	No	Major	A; AC
TSS	mg/L	(13–937)* or 1–36 200	Major	Major	ABCEF
Nutrients					
TN; NH$_4$; NO$_3$	mg/L	0.32–16; 0.01–6.2; 0–16	Minor	Major	ABCE
TP	mg/L	0.06–0.5	No	Minor	BCE
Heavy metals					
Cd; Zn; Beryllium	µg/L	0.2–13; 15–4880; 1.0–49.0	Minor	Major	ABC; ABCDE
Cr; Pb	µg/L	2–50; 2–525	Major	Major	ABC; ABCD
Cu; Ag	µg/L	3.416–355; 0.2–14	No	Major	ABCDE; A
Ni	µg/L	2–70	Minor	Minor	BC
Pt	µg/L	NA	NA	NA	C
Fe; Al; Hg	mg/L	0.08–440.0; 0.1–16.0; 0.05–67	Major	Major	A
Main ions					
Ca; Mg	mg/L	(1–1900)*; (0.03–1.4)*	No	No	B
Cl	mg/L	3.9–669	Major	Major	AB
Na; K	mg/L	(5–474)*; (0.65–3.8)*	Minor	No	B
SO$_4$	mg/L	(5.1–139)*	Minor	Minor	B
Organic substances					
PAHs	µg/L	(0.24–17.1)*	Major	No	ABCD
Pyrene	µg/L	0.045–10	NA	NA	C
Benzo(a)pyrene	µg/L	0.025–10	Major	Minor^{G}	AC
Di-ethylhexyl phthalate; chlordane	µg/L	7–39; 0.1–10	Minor	Major	ACD; A
Heptachlor	µg/L	<0.0002	No	Major	A
Naphthalene	mg/L	0.036–2.3	NA	No	C
Benzo(b and k)fluoranthene	µg/L	0.034–1.9; 0.012–10	NA	Major^{G}	E
MOHs	mg/L	(0.108–6.5)*			B
Oil and grease	mg/L	0.001–110	Minor	Minor	
PCBs	µg/L	0.027–1.1	Minor	Major	ACD
Telrachloroethylene	µg/L	4.5–43	Major	No	A
γ-BHC	µg/L	0.052–1.1	Minor	Major	A
Other XOCs					
Fluoranthene	µg/L	0.03–56	NA	Major^{G}	E
Phenanthrene	µg/L	0.045–10	NA	NA	E
Pentachlorophenol; phenol	µg/L	1–115; 3–10	Minor	Minor	CE; E
Nonylphenol ethoxylates, methyl tert-butyl ether	µg/L	NA	NA	Minor^{G}	C
Organotins					
Tributyltin compounds	µg/L	<0.010–0.078	NA	Major	D
Chloroalkanes	µg/L	0.015–0.05	NA	Major^{G}	D
Herbicides and pesticides					
Pendimethalin, phenmedipham and terbutylazine	mg/L	NA	NA	Major^{G}	C
Glyphosate	mg/L	NA	Minor^{G}	Major^{G}	E
Diuron	mg/L	NA	Major^{G}	Major^{G}	E
Pathogens					
Enterococci	cfu/100 mL	1.2E2–3.4E5	Major	NA	AE
Fecal coliforms; streptococci	cfu/100 mL	0.2–1.9E6; 3–1.4E6	Major	NA	AE
Escherichia coli	cfu/100 mL	1.2E1–4.7E3	Minor	NA	E

A – Makepeace et al. [34]; B – Göbel et al. [3]; C – Eriksson et al. [40]; D – Gasperi et al. [36] and Zgheib et al. [37]; E – Ingvertsen et al. [1]; F – Madrid & Zayas [41] and Paschke [39]; G – Kegley et al. [42]; * Event mean concentrations.

[39,41]. Therefore, in most sampling operations, measurements will be carried out on site, possibly even in situ. Regarding worldwide (ISO), European (EN), or German (DIN) standardized determination methods, several important physicochemical properties of aqueous matrices are temperature, colour, turbidity, pH, electrical conductivity (EC), SS, total organic carbon (TOC) and dissolved organic carbon (DOC).

Use of the surrogate parameter

The contaminant profile of stormwater runoff is broad and the investigation of a large number of parameters is time-consuming and resource-intensive [33,43]. Also, it is challenging to develop cost-effective and robust methods for the continuous measurement of pollutant concentrations [44]. The approach of identifying a set of easy-to-measure parameters which act as surrogate parameters can be used to correlate to water quality parameters of interest [15,43,45]. It is a convenient approach to evaluate water quality directly, without having to carry out resource-intensive laboratory experiments. The adoption of this approach will enable greater quality control in data collection with a decrease in the costs of the collection and measurement of stormwater runoff quality data.

Several studies have been performed to identify surrogate parameters for key urban stormwater quality parameters. Usually, the evaluation of solids and phosphorus in urban stormwater is undertaken by physicochemical monitoring programmes, which sample stormflow for laboratory assessment. Settle et al. [46] investigated the physical and chemical behaviour of solids and phosphorus by univariate and multivariate data analysis techniques. Relationships were developed for SS based on turbidity, dissolved solids based on EC, dissolved phosphorus based on SS and particulate phosphorus based on dissolved solids. Solids can be predicted with higher certainty (0.74–0.93) but phosphorus is less certain by 50%. This study has limited success in developing statistically acceptable relationships, thereby limiting the transferability between catchments. Similarly, Fletcher & Deletic [15] and Grayson et al. [44] considered turbidity as an effective surrogate measure for estimating total suspended solids (TSS). Fletcher & Deletic [15] found that the use of continuously measured turbidity through grab samples had errors in long-term load estimates of less than 5%, though it did not increase more than 10% where routine grab sampling of 3-day interval was used.

Miguntanna et al. [45] identified surrogate parameters for nutrients and solids using rainfall simulation in a small homogeneous residential road area. Good predictive relationships were derived between the selected surrogate [total dissolved solids (TDS), DOC, total solids (TS), TOC, turbidity (TTU) and EC] and the key water quality parameters of interest [dissolved total nitrogen (DTN), total Kjedahl nitrogen (TKN), total phosphorus (TP), TSS, TDS, TS] [45–48]. Though it is not straightforward to find the transferability of the relationship between different geographical locations, the study tried to compare the results with the dataset from near sites that have the typical characteristics of residential, light industrial and commercial areas and their portability was validated. The relationship DTN–TDS and DOC, TP–TS has the highest probability for transferability, whereas TSS–TTU and TS–TTU have medium probability. The relationships TP–TOC, TDS–EC and TS–EC have unsatisfactory transferability.

Discharge measurement

Stormwater discharge data are vital in the sampling programme because they are necessary to assess the contaminant load (e.g. EMC and annual average mass load) and flow-related determinants. Instantaneous flow is to document flow under certain conditions or to develop a database for a stage-discharge rating. Peak flow measurement has wide application in drainage design, flood management and habitat restoration projects where high flows shape the physical habitat of the stream. Continuous discharge data are essential for any watershed project that focuses on the pollutant load. In terms of the estimation of average total mass emission, it is viable to measure continuous flow for grab sampling over a specific time period (day, week, month), instead of instantaneous flow measurement [49,50]. According to the US Geological Survey (USGS), instantaneous discharge measurements and annual station discharge records may produce uncertainty estimates [51]. Comparing weekly, biweekly and monthly grab sampling, monthly sampling produces the best results with this method.

Much of the information regarding flow measurement methods is found in many books and documents such as *Field Manual for Research in Agricultural Hydrology* [52], streamflow measurement in *Handbook of Hydrology* [53] and in selected *Techniques of Water Resources Investigation of the USGS*, e.g., [54,55]. Discharge is estimated either by establishing a relationship with a series of stage and discharge measurements or by following the existing relationship with precalibrated structures such as weirs and flumes. A general description of stage discharge relationships and their development is provided in most applied hydrology texts and USGS documents [52–59]. However, the rapid stage changes, small or high flow rates and short event durations of urban stormwater systems complicate the developing stage of discharge relationships. The uncertainty in continuous stage measurement is mainly determined by stage sensor accuracy, the presence/absence of a stilling well and channel bed conditions [21,60]. The details about uncertainties of different discharge measurement methods are tabulated in the paper by Harmel et al. [20].

The velocity–area method, which measures instantaneous flow and is repeated to cover the entire range of discharges for a particular outfall, is the most commonly used to develop the stage-discharge relationships. The velocity–area method for individual discharge measurement can range in uncertainty from 20% at poor to 2% at ideal or the best conditions. In a good condition with higher equipment accuracy, it can provide an error from 3% to 8% [60]. For the continuous monitoring of stages, it is cost-effective and reliable to install a stilling well/float system [56]. Stage sensors such as bubblers, pressure transducers, non-contact sensors (e.g. radar, acoustic, laser methods) are also commonly practiced to provide continuous stage data [54,56]. With an established stage-discharge relationship, continuous stage data are measured and translated into discharge.

In-stream velocity meters are also commonly used to provide continuous discharge data based on measured velocities and the cross-sectional flow area estimated from stage measurement and cross-sectional survey data. Another technique uses a single instrument to measure both stage and velocity concurrently. The acoustic Doppler velocity (ADV) meters are the most common of these for stormwater or stream flows because they are relatively cheap, cause no head loss and are easy to install and maintain [61]. The accuracy of ADV meters (e.g. Starflow) after calibration was found to be reasonable (<20% at 95% confidence level) in open channels but not necessarily in natural channels [61,62]. However, they are more useful for higher flows without gauging. Flow velocity values by this method may not adequately represent the mean velocity of the entire flow cross section. In this method, velocity is usually measured at 0.6 of depth or at 0.2 and 0.8 of depth to get the mean value. Further, smaller storm events account for the majority of stormwater runoff. It is essential that any device used to measure stormwater flow is capable of accurately measuring at the lower range of the expected flows [63]. Other methods, such as the Manning's equation or the slope area method [53], direct volumetric method and dilution methods are also used to measure discharges. The Manning's equation method estimates discharges based on roughness, slope and cross-sectional geometry, but there is substantial uncertainty (15–35%) depending on the stability and channel uniformity. Therefore, it can be the final alternative for the estimation of continuous discharge measurement.

Selecting sampling methods

The sampling method can be the dominant source of measurement uncertainty in environmental investigations [64], because it contributes to a higher uncertainty in concentration and load estimation though its amount depends on the characteristics of contaminants and whether they are particulate or dissolved [21]. For example, the collection of dissolved N and P samples is much easier than of representative sediment, TN and TP samples, since these constituents are typically distributed uniformly within the channel [65–67]. The variation in these contaminants depends on the rainfall patterns and land use of the catchment. It is also difficult to sample parameters at numerous locations at the same time and the distance between locations matters in terms of time and expense, substantially building uncertainty. Furthermore, constraints of resources, budget and available knowledge restrict the choice of specific sampling methods. These factors are crucial and important drivers while selecting the effective methods of sampling.

Manual or grab/automatic sampling

A sample can be collected manually as a grab sample in the field and transported back to a laboratory for analysis, or with an automatic sampler, retrieved at a later time and analysed in a laboratory. More information on sampling methods can be found in *Standard Methods* [68] and/or *Urban Stormwater BMP Performance Monitoring* [13,63].

Grab samples only represent a snapshot of the water quality at the time of collection. It is easy to observe that the various grab samples may be 10 times greater or smaller than the mean or EMC. Hence, the use of a single grab sample to estimate mass emission rates may have a large error [27]. Unless a sufficient number of grab samples are taken to represent the concentration changes over the period of runoff, and flow measurements are taken at the same time, it is not possible to calculate the pollution load (e.g. EMC) [69]. However, some studies have verified that grab samples can be used for estimating mass load if they are taken for a long time [15,16,27]. Several water quality parameters, such as oil and grease, toxicity and indicator bacteria, are not easily measured by automatic composite samplers [27,70], and therefore require grab sampling. For example, oil and grease in the sample can adsorb in the collection tubing and sample containers, which will cause the EMC to be underestimated. The primary advantage of grab sampling is that set-up costs are small. Nevertheless, collecting grab samples can be more difficult and less practical during storm events for several reasons: (i) the sampling team must wait for rainfall and may miss important parts of a storm event, (ii) they may need to travel a great distance in a short time to reach all sampling locations, (iii) they may not have safe access to sampling locations during rainfall and (iv) because of the cost associated with manually collecting more grab samples [70,71].

Automatic samplers are the most commonly used for stormwater monitoring operations because of their ability to accurately sample parameters. The temporal nature and uncertainty of the timing of storm events usually makes automatic samplers more practical than manual sampling. However, automated samplers are typically limited by their ability to solely collect samples at a single fixed intake point, although movable intakes are seldom used [72]. The automated sampling equipment is also expensive and requires a considerable financial and personnel resource investment for installation, maintenance and repair to ensure proper operation.

Single sample/integrated sampling

While sampling manual or automatic samples, there is always the question of whether a single intake sample is enough to represent the flow over the cross section of the channel. The only known evaluations of a single-intake are available in [65,71–73]. Ging [65] detected dissolved calcium, TP and dissolved and suspended organic carbon among 26 constituents which showed statistically significant differences in median values from integrated and single-intake automated sample collection. Selbig et al. [73] found that by sampling at the bottom of the pipe only, the median concentration of suspended sediment at a fixed point overestimated the actual concentration by 96%, whereas samples collected at three and four points vertically throughout the water column reduced overestimation to 49% and 7%, respectively. Though integrated sampling is applied, the uncertainty of a single sample for a storm event is greater than of multiple samples for the same storm [20,74].

At field-scale sites and in small streams or storm drains, a single sample intake is often assumed to be adequate for sampling well-mixed and/or shallow flows. Indeed, McCarthy et al. [74,75] showed the concentrations of *Escherichia coli* and TN at the bottom and top of the flow in a 600 mm pipe during stormwater events were statistically indifferent, suggesting that one sampling intake at the bottom of the drain would be sufficient for constituents associated with fine particulates in urban stormwater [76]. However, for constituents commonly associated with larger particulates (e.g. TSS and TP), 90% of urban stormwater samples collected from the bottom had equal or slightly higher concentrations than those collected from the top of the water column [74,75]. Uncertainty is higher for TSS and phosphorus than for nitrogen and pathogens when taking a single intake sample [20,74]. As such, caution is still needed even in these constrained well-mixed urban stormwater drains.

Baseline sampling/intensive sampling

The primary goal of baseline monitoring or less intensive sampling is to determine the existing water quality and/or ecological conditions in a receiving water body. This long-term monitoring is primarily done at regular time intervals and, therefore, mainly in dry weather or baseflow conditions where intensive sampling is mainly performed for stormflows. It needs to be cautious about the bias between them because the collection of water samples only during storm events may positively bias annual load estimates, while sampling strategies when baseflow is mainly targeted may underestimate constituent loads.

Dry weather flow or baseflow in many catchments can discharge a substantial quantity of runoff and contaminants [77,78], mainly dissolved components [76,79]. It is often intercepted by groundwater inputs and the variability in nutrients among sites is related in part to the connectivity of the storm drains to upstream sources [78]. Thus, continuous monitoring through at least the baseline sampling of water quality indicators or common contaminants can be particularly useful in those catchments where there are possibilities of intermittent dry weather discharges, illegal discharges, spills or leaks [77].

The sampling of dry weather urban stormwater flows is often conducted using the grab sampling methodology (e.g. [15,16]). The in situ measurement of contaminants indicators (EC, turbidity, ammonical-N, nitrate-N, chloride, BOD, temperature and pH) or contaminants themselves can be applied in stormwater monitoring points using either probes manually or installing at sites. Many studies have revealed that a less intensive sampling programme like grab sampling is required if there is small variation in stormwater quality, but if temporal variation is high, more frequent sampling or an intensive sampling programme is necessary [31,32,77,80]. In the analysis of the coefficient of variance for the quality data range (65 to 3765 observations) in the *National Stormwater Quality Database* (version 1.1, USA) [80], parameters such as EC, oil and grease, TDS, TSS, BOD_5, *E. coli*, coliforms, NH_3, P (mainly particulate P) and dissolved metals (As, Cd, Cr, Cu, Pb, Ni and Zn) have a higher variability than temperature, N (nitrite 'NO_2', nitrate 'NO_3', TKN), filtered or particulate metals.

Several research papers have shown that N, P [65–67] and particulate metals are less variable than other parameters but it depends on the catchment and rainfall characteristics [31,32,77,80]. Nevertheless, stormwater quality parameters during storm events are highly variable within a single site and can vary more when different sites are considered [80,81]. Therefore, the specific variability is difficult to define for the particular parameter. Once less variable parameters are determined through assessment from the existing data for a particular catchment and rainfall range, it is possible to apply less intensive or grab sampling for those less variable parameters.

Discrete/composite-volume-weighted, time-weighted and flow-weighted sampling

Discrete and composite samples can be collected both manually and automatically. Discrete (time or flow or volume interval) samples are single samples collected over a certain period of time, which individually give a snapshot of water quality at a given time and discharge. These samples, if collected over the storm events with flow, provide EMC and site mean concentration (SMC). This sampling method also provides peak concentration during storm events. On the other hand, composite samples are produced by combining samples manually or automatically to provide an estimate of average concentration or total loads. Samples can be achieved as flow-weighted composite (variable volumes of samples proportional to stormwater flow are collected at an equal interval of time increments), volume-weighted composite (fixed volumes are collected at variable time intervals after a constant volume has passed) and time-weighted composite (fixed volumes are taken at equal time increments). The composite sample is usually produced using flow- or volume-weighted sampling [19], which allows determination of the EMC for the constituent(s) of interest.

Composite sampling introduces fewer errors than increasing minimum flow thresholds or increasing sampling intervals, especially for volume-proportional sampling [82–86]. An alternative to collecting automatic composite samples in the field involves manually compositing discretely collected samples in the laboratory [74]. Manual compositing can minimize the errors associated with sampler failure during an event (i.e. missing one sample in a volume-proportional, composite strategy).

Purposes of sampling in selecting sampling methods

Many countries have policies, laws and regulations for stormwater monitoring. According to the national or regional goal, the monitoring of stormwater may have different purposes. Consideration of the specific objectives for monitoring is the first step to determine how the sampling programme needs to proceed. The common objectives are (i) assessing maximum discharge and/or concentrations for comparison with the maximum limit of consent conditions, (ii) assessing mass load and/or EMC and/or SMC, (iii) assessing temporal variability, (iv) identifying sources of particular contaminants at the catchment and (v) assessing stormwater treatment performances.

In countries where stormwater management is at an initial phase and where stormwater treatment facilities still need to be retrofitted, the main concern is on the first two objectives. According to the first objective, the downstream receiving environment quality is of the greatest interest. In order to compare measurements of concentration directly to consent limits or water quality guidelines, the sample(s) measured accurately should represent the poorest water quality discharged during a storm. The second objective is more common in many stormwater monitoring programmes because the average concentration and annual emission loads are always an issue for the receiving water bodies or estuary. This provides a scope for comparing sites and modelling the benefits of stormwater treatment facilities. Data from the monitoring to achieve the third objective are mainly essential for the calibration and validation of catchment scale models, but also for comparison between sites and modelling benefits. The fourth objective has more in-depth investigation to determine the extent of contamination and trace the likely sources. It requires multiple sites upstream and downstream of the suspected sources of contaminants. Samples are collected for the same storm events to compare between sites. The fifth objective is to evaluate the performance of stormwater treatment facilities relative to the design. In achieving these objectives, the monitoring programme usually targets the estimation of peak flow/concentration, EMC, SMC and/or mass load and temporal variability and/or their combinations. Therefore, four purposes are possible: (i) peak flow/concentration (P1), (ii) temporal variability (P2), (iii) EMC and/or SMC and/or event mass load (P3) and (iv) annual mass load (P4), and their combinations: CP1–P1 and P2, CP2–P3 and P4, CP3–combined purpose not including P4, CP1 and CP2, and CP4–combined purpose including P4 but not CP1 and CP2. Based on these purposes and the required accuracy, an appropriate sampling method can be selected from different sample collection methods (grab sampling, discrete sampling, composite sampling, combination of discrete and composite sampling, combination of grab and composite sampling, etc.), which are illustrated in the section ‘Results and discussion’.

Sampling threshold

The increase in the sampling threshold introduces substantial uncertainty from 2% to 20% for low to high thresholds during storm sampling [20,74,82], which can again increase to 35% when not extrapolating flow and concentration outside the sampling period. Therefore, the threshold needs to be set such that the sampling method could address the entire storm event.

Typically, the sampling of storm events requires more than 2 mm of rainfall, as a lesser amount will not result in runoff due to evaporation and depression storage [87]. The intensity greater than a threshold value of 5 mm/h was considered as the start and end of a selected rainfall event since the rainfall intensity lower than 5 mm/h has no significant effect on pollutants wash-off due to low kinetic energy [88,89]. Though this depends on catchment sizes and topography, generally, the threshold is provided with rainfall measurement. However, the threshold point is determined by changes in flow levels and is ensured by the change in the turbidity, EC or temperature for automatic sampling.

Sampling frequency and timing

The frequency of sampling determines the number and the interval of samples that need to be taken for stormflow and baseflow. It mainly depends on the purposes of sampling as to whether it is to assess peak flow/concentration, EMC and mass load, SMC and annual load or temporal variability.

Several studies have confirmed the statistical theory about sampling that the smaller the sampling interval (the higher the number of samples), the better the actual population characteristics and the lower the uncertainty [83–85,90], as can also be noted in Table 3. King & Harmel [84] and Harmel et al. [91] provide guidance on selecting time and volume intervals for automated sampling on small catchments. Moreover, based on averages from the 300 storm events, King & Harmel [84] concluded that time-discrete sampling at a 15-min interval or less was required to produce a load estimate that was not significantly different ($\alpha = 0.05$) from the total pollutant load. The same accuracy can be obtained for discrete flow-paced sampling at or above

Table 3. Discrete and composite sample collection frequency and timing with relative uncertainty [20,21,74,84,92]

Frequency and timing	Uncertainty[a]	Reference
Discrete flow-interval sampling strategies:		
0.2–1.25 mm	±0% to 22%	A, B
0.5 mm at initial runoff and 1.5–2.5 mm for remainder	<10%	C
1–2.54 mm over storm duration for small storm events	Significantly indifferent at $\alpha = 0.05$	D, E
1–2.54 mm at initial runoff and 6 mm at remainder for medium to large storm	Significantly indifferent at $\alpha = 0.05$	D, E
6 mm for large storm	Significantly indifferent at $\alpha = 0.05$	D, E
12 flow-interval discrete samples	Small bias and standard error	F
Discrete time-interval sampling strategies:		
5 min, discrete	±0% to 18%	A, E
10 min, discrete	±0% to 40%	A
15 min, discrete	Significantly indifferent at $\alpha = 0.05$	D, E
30 min, discrete	±3% to 72%	A, E, B
120 min, discrete	−15% to 13%	E, B
42 time-interval samples	Small bias and standard error	F
Time-interval composite sampling:		
5 min, with up to six composite samples	−5% to 4%	E, B
30 min, with up to six composite samples	−32% to 25%	E, B
60 min, with up to six composite samples	±0% to 19%	H
120 min, with up to six composite samples	−65% to 51%	E, B
5–360 min, with up to three composite samples	±1% to 33%	E, G
5–360 min, with up to six composite samples	±5% to 50%	E, G
Flow-interval composite sampling strategies: *f*(flow interval)		
2.5–15 mm, with up to three composite samples	±0% to 5%	E, G
2.5–15 mm, with up to six composite samples	±0% to 8%	E, G
1.32, 2.64 and 5.28 mm, with up to six composite samples	−9% to +3%; median ±0.4	I, G

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[a] Error estimates are presented as their ±% range for bidirectional error or as their actual % range.
A − Miller et al. [83], B − Harmel et al. [20], C − McCarthy et al. [74], D − King et al. [92], E − King & Harmel [84], F − Leecaster et al. [16], G − Harmel et al. [21], H − Miller et al. [93] as cited by Harmel et al. [21], I − Harmel & King [85].

volume-proportional depth intervals of 2.5 mm. King et al. [92] developed a procedure to determine sampling intervals based on catchment and constituent characteristics. Although they concluded that volume-proportional depth intervals up to 6 mm may be appropriate in certain conditions, smaller intervals (1–2.54 mm) are more widely applicable. These smaller intervals allow smaller storm events to be sampled and moderate-to-large storm events to be sampled more intensively with little to no increase in uncertainty, especially if composite sampling is utilized. The flow-stratified approach had a smaller absolute error than did the time-based approach when an equal number of samples was obtained [84] and thus many studies have recommended the flow-stratified approach over the time-based approach [83–85,94,95].

If the purpose of sampling is to measure the peak concentration, the sampling interval over the storm events may be different. The peak concentration may occur at the beginning of a storm event (i.e. during the ‘first flush’), with the peak flow [96–98], or even at the end of the storm event [99]. There is some evidence that constituent concentrations are more variable on the initial portion of storm events where sometimes the first flush exists [95,99]. McCarthy et al. [74] used every 0.5 mm to more adequately capture initial conditions and every 1.5–2.5 mm for the remainder of the event. They showed that the estimated error between such a sampling regime and an estimated ‘true’ value of the EMC for turbidity in a stormwater system was less than 10% across the four sites observed.

The sampling programme mostly concerns a lesser number of samples because a rise in the number of samples considerably increases the cost for sampling and analysis and not necessarily aggregates uncertainties. The variations in stormwater flows and constituent concentrations inherently govern the sample numbers in the sampling regime [31,32,77,80]. For example, a constituent that does not vary considerably during stormflow will require significantly fewer samples to characterize. Many monitoring programmes suggest performing composite sampling. This method increases sampler capacity, making it a valuable and cost-saving alternative. Composite sampling with two or four aliquots per bottle reduces sample numbers to 50% and 25% of those are collected by discrete sampling. This method introduces less error than discrete sampling [82,84,85]. However, composite sampling reduces information on the distribution of within-event constituent behaviour, which limits the study of various transport mechanisms. It is a powerful option for making a single composite sample from flow interval subsamples for the entire event duration [19,84,100]. In single composite samples (if 16 L of bottle capacity), 80 (of 200 mL) to 160 (of 100 mL) of subsamples can be composited but this depends on the storm volume.

The constraint to perform discrete sampling has introduced composite sampling, but the cost is again considerable, though it reduces the number of samples for analysis. In countries where budget is always a constraint, grab sampling is an alternative. It is challenging to represent all intra- and interstorm event characteristics. However, many studies have tried to provide an effective frequencies and timing process for grab sampling as presented in Table 4.

Table 4. Grab sample collection frequency and timing with relative uncertainty. NA, not analysed

Frequency and timing	Specific condition	Accuracy	Reference
Single point, random time	NA	Uncertainty (±25% dissolved; >50% suspended)	Slade [59]; Harmel et al. [20]
Single random sample within storm Single random sample 1 h after commencement of storm Routine single sample at 3-day interval not responding to storm	Large catchment area	Around 10%	Fletcher et al. [15]
12 random samples	Large catchment basin, variable contaminant, wet season	Bias and standard error >12 flow-interval discrete samples but <42 time interval samples	Leecaster et al. [16]
Single sample after 1–6 h of runoff (depending on rainfall and site-specific characteristics)	Impervious highway sites, mainly for oil and grease, i.e. not correlated with TSS	Close to flow-weighted composite sample	Khan et al. [70]
Single sample middle of storm	For TSS and Zn	Representative	Lee et al. [27]

Fletcher et al. [15] collected a single grab sample within the storm event randomly and 1 h after the commencement of the storm for seven storms. They compared the mass load or SMC of TSS, TN, TP, Pb and Zn with true load and detected around 10% difference from true load. On the other hand, a routine grab sampling campaign which does not specifically respond to storm events showed that the errors increased with the sampling interval and a 3-day interval was required to maintain errors within 10% of the continuously measured load of TSS. They concluded that autosamplers were not essential if only long-term load estimates were required. However, they did not show the variability of contaminants within the storm events and most of the catchments studied by them are of large areas, which may provide long-period hydrographs and pollutographs. If the variability of contaminants is not high, the samples at any time within a storm do not significantly affect mass load. This limitation was overcome by Leecaster et al. [16] who compared the flow interval, time interval and simple random sampling to estimate EMCs and mass load as well as SMCs and annual mass load. They suggested a minimum of 12 flow-interval samples (Table 4), using a volume-weighted estimator of mass emissions, to characterize a storm event most efficiently with a small bias and standard error. They showed that 12 simple random samples are less accurate than 12 flow-interval samples but these provide a better result than 42 time-interval samples. In this study, the catchment basin is large (where peak flow occurs 3 h after the commencement of the storm due to rain 0.8 cm/h), constituent variability is high and the study period is unnaturally wet [16,101].

Khan et al. [70] examined 22 oil and grease pollutographs from small impervious highway sites to determine when a single grab sample most closely approximates a flow-weighted composite sample. They concluded that collecting a single grab sample 1–6 h after the beginning of runoff within a storm more closely approximates the EMC than sampling earlier or later in the storm. The results depend on storm characteristics (total rain and storm duration) and site-specific characteristics (antecedent dry days and total rain). Samples early in a storm event should be collected if the peak or maximum concentrations are desired. This result is particularly for oil and grease, which have weak correlation with SS. However, a similar conclusion is suggested by Lee et al. [27] for TSS and Zn. They emphasize that the sampling time during the storm event will affect results for grab samples, since the samples collected early in the storm will have higher and those collected late in the storm will have lower concentrations than the EMC. They agreed with the Khan et al. [70] conclusion and recommended grab sample collection in the middle of the storm which is more representative, however, the appropriate time is site-specific and needs to be investigated. They added that the samples collected early in the season would better represent maximum concentrations.

Sampling frequency and time for dry weather flow

Dry weather flow samples were taken manually at biweekly or monthly intervals (a monthly interval can be specially adopted halfway through the study) to characterize baseflow and facilitate the determination of sources (groundwater, illicit discharges, etc.) [102]. Most of the dry weather flow samples are taken after a period of at least three days without rain [103,104] when the runoff does not exceed the minimum sampling threshold as explained above [105]. The monitoring period should be sufficiently long so that potential seasonal effects on water quality can be investigated and can represent reasonably average flow conditions. The sampling frequency should also ensure that the samples are statistically independent. To account for seasonal variability, one sample per month can be collected [106] over a twelve-month period. A technique by NSW EPA [107] can be applied to determining the minimum number of samples for a desired statistical confidence level. The variability of concentrations has a large influence on the accuracy of certain sampling strategies on load estimations. For example, a pollutant whose concentration varies quite considerably during dry weather flows cannot have its weekly or monthly loading accurately estimated by one random sample per day. On the other hand, a pollutant that is fairly constant during dry weather periods could have its load accurately estimated using the monthly sampling regime [77].

Number of storms

Stormwater constituent concentration varies between storm events and it is essential to monitor more than one event in order to adequately characterize the site [108]. Due to time and cost constraint [109,110], the determination of the minimum number of storm events that should be sampled is necessary to estimate the pollutant mean concentration or SMC, peak concentration and temporal variability for model calibration within a given level of uncertainty [27,110–112].

Some researchers have attempted to quantify the number of storms required to adequately characterize the site (see Table 5). In 1993, Smoley [113], cited by Pandit & Gopalakrishnan [105], put forward a concept of representative storms that could be used to derive the approximation of SMC. The minimum number suggested was three storms, which have characteristics such as

Table 5. Number of storms for sample collection with relative accuracy

No. of storms	Specific condition	Accuracy	Reference
Minimum three	(i) The antecedent dry period >72 h, (ii) the storm depth >2.5 mm and (iii) the storm duration and depth <50% the average storm size	Small bias	Smoley [113] as cited by Pandit & Gopalakrishnan [105]
Seven storms per year (~50% of the storms)	Mass emissions or concentration estimate	10% uncertainty	Leecaster et al. [16]
Three storms per 5 years	Mass emissions or concentration estimate	20% uncertainty	Leecaster et al. [16]
Seven medium and large storms per year with 12 random samples	Mass emissions or concentration estimate	~accurate (<10% uncertainty)	Leecaster et al. [16]
Minimum of 5–7 storms/avg six storms	SMC estimate (of phosphorus)	Relatively accurate/ 40% less cost of 12 storms	May & Sivakumar [110]
Minimum of 6–8 storms (5–6 during wet season and 1–2 during dry season)	SMC estimate	Relative standard error <20%.	Maniquiz-Redillas et al. [111]
Max 10 storms	Temporal variability for model calibration, SMC prediction	Narrower confidence intervals	Mourad et al. [114]
At least 10 storms	Temporal variability for model calibration, EMC prediction	Narrower confidence intervals	Bertrand-Krajewski [115]

(i) the antecedent dry period must be greater than 72 h, (ii) the storm depth should be greater than 2.5 mm and (iii) the duration and depth of the representative storm should not be greater than 50% the size of the average storm at the catchment. These characteristics reduce the bias due to outliers in SMC calculation. However, this method may not be efficient in all circumstances because either whole storm events need to be captured to sort out representative storms or they require long-term rainfall data, but the average still may not be static as it varies from year to year.

Leecaster et al. [16] concluded that sampling seven storms (approximately 50% of the storms in a typical year) is the most efficient method for attaining small confidence interval width with 10% uncertainty for annual concentration. When coupled with the simple random sample (at least 12 per storm) of medium and large storms within a season, the ratio estimator most accurately estimated the concentration and mass emissions and had low bias over all of the designs. Sampling three storms per year allows a 20% trend to be detected in mass emissions over five years. The results are mainly based on TSS concentration, which they found highly correlated with other constituents such as trace metals, TOC and TN. It was observed that in most studies SS was often used as the predominant pollutant monitored in determining the errors associated with the number of sampled storms [16,114,115]. May & Sivakumar [110] used phosphorus data from 17 urban catchments to derive the optimum number of storms by evaluating the balance between total sampling cost and the degree of uncertainty. Total phosphorus is log-normally distributed [116]. It is monitored as a predominant variable in the Nationwide Urban Runoff Program study [110]. The study suggested that a minimum of 5–7 storms was sufficient to derive a relatively accurate estimate of SMC. However, it was concluded that the number of storms varied slightly depending upon the catchment and the error measure analysed. The study also deduced that monitoring six storm events would be approximately 40% cheaper than monitoring 12 events.

It is also essential to associate the degree of uncertainty and variability in the number of storms according to seasons and water quality parameters. Maniquiz-Redillas et al. [111] showed that a minimum of 6–8 storm events were adequate to estimate the SMC of TSS at a relative standard error of less than 20%. The standard error significantly increased from 40% to 65% when the number of storms decreased from five to three for TSS, TP, COD and BOD, while TN and DOC need 8–10 storm events to reduce the standard error by only 30–40%. During most of rainfall (in spring and summer), the storm event sampling was preferably to be conducted five to six times, but only once or twice during the autumn and winter seasons.

Some researchers have analysed the number of storms using stormwater models. Mourad et al. [112] analysed SS data from a combined sewer network to determine the sensitivity of stormwater quality models to calibration data. When fewer than 10 storms were used for model calibration, they observed that an SMC model produced narrower confidence intervals associated with total load predictions than regression models and a build-up wash-off model. In contrast, Bertrand-Krajewski [115] suggested that confidence intervals associated with EMC predictions were very large when fewer than 10 sampled storms were used to calibrate multiple regression models. Mourad et al. [117] conducted another study using BOD, COD and SS data from 13 out of the same catchments to estimate the SMC as a flow-weighted mean. The authors concluded that it was not possible to identify a universal minimum number of events to be monitored at a catchment that would approximate the SMC with a specified level of uncertainty.

RESULTS AND DISCUSSION

Tables 1–5, prepared based on literature reviews, present the approaches to site selection, sampling parameter selection and sample collection systems. The results from these reviews are summarized below as suitable sampling approaches. This information was used to create an efficient sampling programme that is presented in Table 6. Selected parameters in the watershed of Tallinn are described in Table 7 for which three sampling sites are selected out of 66.

Suitable sampling approaches

Site selection

Table 1 presents a reviewed approach of pre-screening, screening, quick scan and final selection of sites. The selection of sites is important since not all sites can be monitored due to difficulties in the mobilization of the staff and equipment as well as financial constraints. Moreover, it is applicable and cost-effective to categorize sites into intensive and less intensive sites.

Selecting potential parameters

In reviewing the broad range of parameters, the list of parameters is prepared as shown in Table 2, which includes selected priority pollutants and physicochemical parameters. These parameters have a major impact on

Table 6. General monitoring programme

Aspect	Sites A requiring intensive sampling	Sites B not requiring intensive sampling	References
Location	At point of discharge into receiving environment; and/or downstream of discharge in well-mixed area	At point of discharge into receiving environment; and/or downstream of discharge in well-mixed area	Table 1
Flow measurement	Preference 1* or Preference 2* (required as a surrogate for flow hydrograph) or Preference 3*	Automatic stage measurement with surrogate parameters	Section ‘Discharge measurement’
Sampling method for stormflow			
Sampling mode	Volume/flow-proportional automatic, but grab samples may also be feasible in some circumstances (e.g. short distance to sampling site, for oil and grease parameters)	Grab sampling	Section ‘Selecting sampling methods’
Mimimum threshold	At least three days and/or rainfall intensity 2 mm/h	At least three days and/or rainfall intensity 5 mm/h	Section ‘Sampling threshold’
Sampling frequency	Sample collection is more frequent during periods of higher or at initial runoff (0.5 mm) and greater interval for remainder (1.5–2.5 mm) as specified by McCarthy et al. [74]	Within first 1 h for peak concentration during first flush and seasonal first flush; within 1–6 h of storm event for EMC, SMC or annual loads as specified by Lee et al. [27] and Khan et al. [70]	Tables 3 and 4
Number of samples	At least 12 discrete samples per event; at least one composite sample	At least one sample for peak flow; at least one sample for EMC, SMC or annual loads	Tables 3 and 4
Storm size	At least seven medium and large storms	Seven medium and large storms	Table 5
Parameters	Primary and secondary parameters	Primary and secondary parameters	Tables 2 and 7

Preference 1*: stage-discharge measurement with the precalibrated structure installed preferably on the stable channel; Preference 2*: stage measurement using stillwell; Preference 3*: velocity area method using the acoustic doppler flow meter.

Table 7. Recommended parameters for the monitoring programme in Tallinn

	Primary parameters	Secondary parameters	Adopted from
Physicochemical	pH and SS		A
	EC, TTU, TDS, TOC and DOC		B
Micropollutants	Hydrocarbon,		A
	PAH and PCB	DEPH, phenols, benzo(a)pyrene	C
Oxygen demanding compounds	BOD_7 and COD		A
Nutrients	TN and TP		A
Metals	Zn, Cu, Pb	Cd, Cr, Hg	AC
Ions	Cl^-		C
Pathogens	*E. coli*, enterococci		D
		Faecal coliform	C

A – Estonian Water Act, Regulation No. 99; B – surrogate parameters; C – major pollutants on literature (from Table 1); D – potential parameter for good bathing water quality (EU and Estonia).

either human or aquatic life or both. It is a contaminant profile where each parameter from different papers is considered as a potential element that needs to be monitored. These parameters are area-sensitive since a potential parameter at one place might not be potential at another place. However, the most pronounced parameters noticed in above literature are physicochemical (pH, TSS), nutrients, heavy metals (Cd, Cr, Cu, Pb, Zn), PAH and PCB. Therefore, at a very early stage of monitoring when there is no sufficient data for parameters, this list can be used to compile a minimum set of parameters that have major impacts on the local area.

While compiling a minimum set of parameters, the approach of surrogate parameters to reduce the cost of monitoring can be applied. Several researchers have noted that EC, TTU, TSS, TDS, TOC and DOC have the potential to act as surrogate parameters for other key water quality parameters such as solids, nitrogen and phosphorus [15,44–46,98]. It is possible to apply the combined sampling of surrogate parameters measured continuously and target parameters measured intermittently. It will significantly reduce the cost of measuring the concentration without compromising accuracy. Should this method not be affordable, the continuous measurement of surrogate parameters can be applied and the concentration of target parameters can be estimated using the correlation coefficient. The result may provide considerable uncertainty but the grab-sampled concentration can be used to verify them.

In Finland, the more recent monitoring programmes used in the projects ‘Stormwater-Research Programme (2008–2010)’ [118] and ‘Urban Laboratory for Sustainable Environment (2012–2014)’ [119,120] include the above-mentioned parameters as water quality variables for study. Likewise, in Lithuania, the subjects of research were usually common water parameters (BOD, pH, TSS, COD, hydrocarbons) [121] and metals (Cd, Cu, Pb, Zn) [122,123].

Discharge measurement

In general, continuous discharge measurement is essential, especially for the estimation of mass load and runoff volume. Uncertainty is smaller for stage discharge measurement with the pre-calibrated structures preferably installed on the stable channel. They are highly recommended because they have an associated stage-discharge relationship and provide reliable and accurate flow data for a number of years with minimal maintenance [20,59]. Monitoring stillwell is also a good option for stage measurement, as it is cost-effective and reliable for the long run. If there is location constraint, the final option will be the velocity area method using an ADV meter. This methodology in concept is excellent for determining an accurate discharge because of the ability of the flow monitor to account for variable and backwater conditions.

Sampling mode

Automatic sampling is recommended for continuous measurement as it reduces a human error but grab sampling also has substantial certainty when properly applied. Grab sampling is mostly preferred for certain parameters such as oil and grease. The parameters that do not have large variation throughout the storm can be monitored using grab sampling or baseline sampling. A single intake sample is taken at the well-mixed flow because the concentration can vary over the cross section of flow.

Flow interval/proportional sampling is superior to time interval/proportional sampling and grab sampling. However, whether to proceed with discrete or composite sampling or a combination of both depends on the purpose of sampling. Figure 1 shows the flowchart to decide the sampling method according to the purpose of sampling.

The most appropriate sampling methods for attaining purposes are selected based on accuracy explained in the sections ‘Selecting sampling methods’ and ‘Frequency and timing of sampling’. Those methods are presented prioritywise in Fig. 1 as i – first priority, ii – second priority and iii – third priority. Discrete flow proportional sampling is preferred for assessing peak flow/concentration and temporal variability, while composite flow proportional sampling is preferred for estimating EMC and SMC, though some parameters such as oil and grease need grab sampling. Dry weather flow and concentration are not ignored and can be monitored by grab sampling, which is used to estimate mass emission. Some studies have found that grab sampling can be used to estimate EMC, SMC and mass load, but it should be applied as the last alternative when it is limited by budget and resource constraints because the results depend on the catchment and contaminant properties. In Lithuania, sampling methods were changed from grab sampling irrespective of the storm event at early research [121] to flow proportional composite sampling at recent research [122]. More up-to-date funded projects in Finland have used flow proportional composite sampling methods in order to attain higher certainty of EMCs and pollutant loads [118–120,124]. Nevertheless, it is not always the case when available resources are limited and there are more than just a few sites involved. The optimal programme has to be selected to meet these resources. The details of this programme are discussed below in the section ‘An optimal and effective sampling programme’.

Sampling frequency

Table 3 presents the frequencies for discrete and composite sampling, whereas Table 4 presents frequencies for grab sampling to choose based on uncertainty and resource availability. When analysing discrete and composite sampling frequency and timing, it is clear from Table 3 that the uncertainty decreases as the sampling frequency increases. Flow interval sampling can be recommended as the first priority of sampling. Indeed, increasing frequency aggregates the number of samples, which increases the cost of analysis. Therefore, sampling intervals depend on how much degree of certainty is required and how much can be afforded. To achieve a sufficient degree of certainty at a reasonable cost, the flow interval sampling frequency provided by King et al. [92] and King & Harmel [84] can be recommended for discrete sampling when the purpose

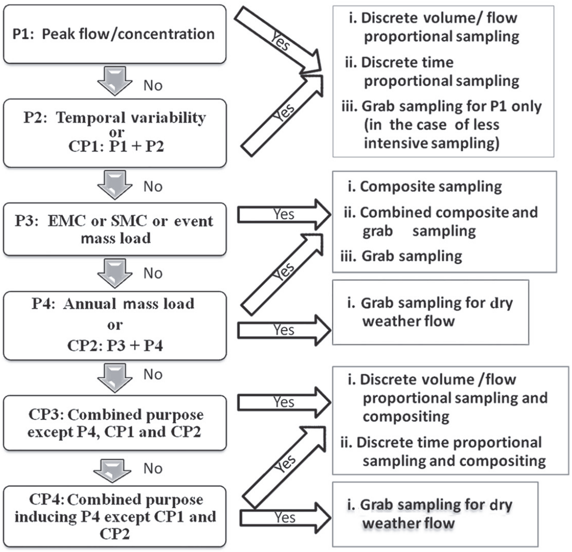

Fig. 1. Sampling method according to different purposes of sampling. P1–P4 are purposes and CP1–CP4 are combined purposes.

is estimating the peak flow/concentration, temporal variability and/or their combinations. A comparatively better sampling for the estimation of EMC, SMC and mass load is flow interval composite sampling. It can also be noted from Table 3 that uncertainty decreases as the number of composite samples decreases. Harmel et al. [20], King & Harmel [84] and Shih et al. [100] have noticed that a single composite sample for the entire event can provide sufficient accuracy.

If the budget is not sufficient to proceed with the above recommended discrete and composite sampling, the 12 flow interval discrete sampling method can be employed (as in Table 3) for the purpose of EMC, SMC, mass loads and their combination, which provides a small bias and error and is comparatively easy to apply on site [16]. If manual sampling has to be performed, 12 random samples (as in Table 4) could be the first priority [16] in comparison to other grab sampling frequency and timing because it could address the variability of contaminants in a storm event and rainfall effects. The final alternative, if the first priority is not affordable, is to take a grab sample between 1 and 6 h of runoff or in the middle of the storm.

Number of storms

Review of papers for the optimum number of storms to be sampled as in Table 5 showed that many researchers have recommended that seven storms are appropriate for low error estimate of EMC, SMC and mass emissions. As May & Sivakumar [110] found, it can be substantial increment of cost once the sampling is increased from 6 to 12. In such a condition, seven storms per year does not abruptly increase the cost of sampling. However, for temporal variability to calibrate models, a maximum of 10 storms can be recommended. If grab sampling has to be performed further to reduce the cost of sampling, 12 random samples for seven medium and large storms over the year can be chosen.

An optimal and effective sampling programme

In this study, the usual condition is considered, which means (i) the purpose of sampling is common, i.e. to obtain the concentration in order to compare with the permissible limit as in the Tallinn stormwater monitoring system and (ii) there is constraint of budget and resources. Table 6 presents the general monitoring programme on the usual condition based on the results from literature reviews. According to Lee et al. [27] and Langeveld et al. [28], it is more reasonable and cost-effective to use two sampling methods. One is intensive sampling for the final selected sites (sites A) and the other is baseline or less intensive sampling for sites (sites B) selected after pre-screening and screening, excluding sites A. The procedures for selection of sites A and sites B are described in detail for Tallinn in the section ‘Site selection in Tallinn’. The selected parameters can be categorized into primary parameters requiring intensive sampling and secondary parameters requiring less intensive sampling. Details of these parameters are discussed in the section ‘Sampling parameters in Tallinn’ as in Table 7. The sampling method depends on the purpose of sampling as mentioned above. The sampling programme is to capture the peak concentration or the poorest concentration during storm events. Due to the behaviour of peak concentration, it is ideal to collect a large number of samples throughout the storm event, but it is expensive to do such sampling in all outlets. Therefore, it is practical and reasonable to perform intensive sampling for sites A and grab sampling for sites B as shown in Table 6.

Though the purposes are different from estimating EMC, SMC and annual loads, the samples collected for peak concentration can be composited manually or automatically during intensive sampling in order to use them to calculate EMC, SMC and annual loads. For intensive sampling, grab sampling is not recommended, unless there is a single site and short distance to the site because it is difficult to mobilize the sampling staff and equipment to different sites at the same time. To find the peak concentration, grab sampling or less intensive sampling can be performed in sites B where a single sample is taken within 1 h of storm commencement during the first flush or seasonal first flush. It is recommended to install automatic water level measurement devices, which can also measure some surrogate parameters continuously. Due to the similar conditions, this general sampling programme can be recommended for the Tallinn watershed.

APPLICATION OF THE SITE AND PARAMETER SELECTION APPROACH

Site selection in Tallinn

According to the Estonian Nature Information System [125], 66 stormwater outlets exist in Tallinn. The methodology by Langeveld et al. [28] can be applied to select appropriate locations (see Table 1). These outlets can be divided into three categories based on the receiving bodies after final discharge as shown in Fig. 2. Forty-eight outlets that discharge water directly into the coastal sea are included in category I, seven outlets that discharge to the watercourse are in category II and 11

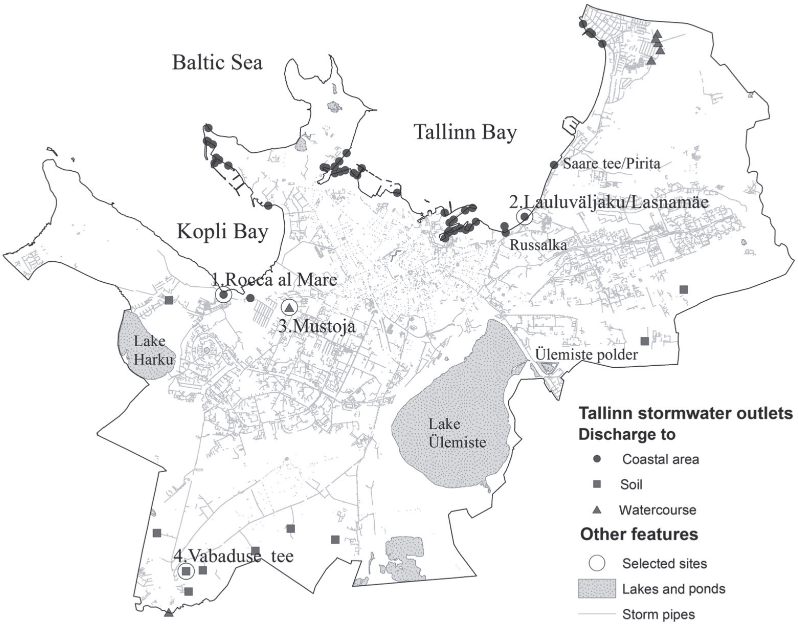

Fig. 2. Stormwater outlets in Tallinn.

that discharge to soil in the Tallinn catchment area are in category III. During pre-screening, 14 storm outlets can be selected from 66 storm outlets (10 in category I, 2 in category II and 2 in category III) on the basis of general suitability and representativeness. The main criteria for this selection are outfall location, catchment properties and special activities within the catchment as described in Table 1: for example, selecting one from each group of outlets near to each other; the Mustoja basin has a combination of industrial, commercial and residential area; the Saare tee basin has mostly residential areas with private houses; Lauluväljak is a densely residential area; Rocca al Mare has the impact of the zoo; Russalka has discharges from the Ülemiste polder. When these outlets are compared to personal safety, equipment security and accessibility during the screening phase, they reduce to eight storm outlets (6–I, 1–II, 1–III).

For a quick overview, the database of stormwater quantity and quality is available for six major storm outlets: Saare tee, Lauluväljak, Russalka, Ülemiste polder, Rocca al Mare and Mustoja Paldiski Road. The monitoring programme was organized by the Tallinn City Environment Department. Tallinn University of Technology, the Environmental Engineering Department and AS Tallinna Vesi got involved in 2012. The monitoring frequency is six times per year. Twelve parameters such as flow, temperature, conductivity, oxygen, BOD, SS, TN, TP, PAH, *Escherichia coli*, enterococci and Salmonella are measured and grab sampling is used. SonTek Flowtracker is used for the instantaneous flow rate measurement. Grab sampling is carried out randomly not responding to storm events. Analysis of data from 2005 and 2008–2012 shows that the average concentration for most of the parameters does not exceed the permissible level, aside from microbiological parameters, but the variation in the concentration and confidence interval is high [126]. The concentration exceeds the permissible level several times in Saare tee, Rocca al Mare and Mustoja. The databases for categories II and III were retrieved from the Estonian Nature Information System [125], which have quarterly data examined for three years.

The system dynamics of the outlets is still uncertain because the samples may not address storm events. However, considering the representativeness of the catchment basin and special activities, the final selection of locations may include four outlets (2–I, 1–II and 1–III) where the measuring instruments can be installed for intensive sampling and which are grouped as sites A similar to the recommendation by Lee et al. [27]. Those possible four outlets (as in Fig. 2) for sites A are Lauluväljak and Rocca al Mare of category I, Mustoja of category II and Vabaduse tee of category III. The other four outlets in category I can be installed with a less intensive sampling method and are grouped as sites B.

Sampling parameters in Tallinn

The Estonian Water Act, Regulation No. 99 of the Government of Estonia, 1 Jan 2013, 'The wastewater treatment and requirements of wastewater and stormwater discharges into the receiving water bodies; wastewater and stormwater pollutant thresholds; and compliance verification measures' provided limit values for SS – 40 mg/L, hydrocarbon – 5 mg/L, BOD_7 – 15 mg/L, COD – 125 mg/L, TP – 1 mg/L and TN – 45 mg/L in stormwater runoff [127]. Wastewater and stormwater effluents should not worsen the state of aquatic and terrestrial ecosystems. Trace metals (Zn, Cu, Pb, Cd, Cr, Hg) are also considered potential pollutants [128]. The European Union, as well as Estonia, has restricted microbiological parameters exceeding 1000 cfu/100 mL *E. coli* and 400 cfu/100 mL enterococci for good bathing water quality [129,130].

Generally, many other potential parameters are found in urban stormwater. As in Table 2, several reports mentioned metals (Zn, Cu, Pb, Cd, Cr), ions (Cl^-), micropollutants (PAH, PCB, DEPH) and pesticides, which are prevalent in urban stormwater and hazardous to either human or aquatic life; however, their quantity depends on the upstream rainfall and catchment characteristics. Moreover, surrogate parameters can be supplemented, as they can be measured in situ. Such surrogate parameters are EC, TTU, TDS, TOC and DOC, and they are applicable to estimating target parameters that reduce the burden of intensive sampling and expensive analysis. It is essential to ensure that stormwater should not either contain hazardous pollutants or their content should be less than the acceptable limit.

These parameters are categorized into primary and secondary parameters as in Table 7. The primary parameters mainly include those that are mandatory to monitor and adopted from the Estonian Water Act, Regulation No. 99. In addition, the parameters that have a potential risk and a great chance of occurrence in stormwater are added to this category. Secondary parameters include those that pose a potential risk to human or aquatic life if they are present in stormwater, but their presence often depends on upstream catchment characteristics and special activities. Primary parameters need comparatively more intensive sampling than secondary parameters. These recommended parameters can be used for all of Estonia according to local conditions.

CONCLUSION AND RECOMMENDATIONS

Sampling strategy is an important aspect of the monitoring programme through which quality stormwater data can be obtained. By reviewing the effectiveness of best-practiced sampling procedures in different research papers, site selection approaches, selection of monitoring parameters and the sample collection system are compiled. Site selection approaches have minimized the number of sites to monitor, the selection of parameters has fixed the potential parameters and options in sampling methods have provided the decision capability to choose the one which balances resource availability and effectiveness. Based on these reviewed approaches, the possible stations and sampling parameters were assessed for Tallinn. In addition, an optimal and effective sampling programme was developed which is recommended for stormwater monitoring in Tallinn. This sampling programme, in general, is affordable, applicable and effective.

The study is based on the literature reviews and has compiled the effective approaches but the uncertainties are not analysed through statistical measures. The real cost is not incorporated to analyse affordability, thus there is a possibility of further study to provide cost-based scenarios. Effectiveness is evaluated based on available uncertainties. However, there are options to choose between the approaches but still an appropriate approach depends on the land use and rainfall patterns in the watershed. The optimal sampling programme, though containing cost-effective methods, does not provide higher certainty in all cases. In addition, the reviews on passive sampling are not discussed in this paper. Nevertheless, the study has attempted to use an approach with a smaller error and low-cost sampling. It provides decision capability to select the suitable monitoring programme in terms of effectiveness, applicability and affordability such that it can be used to obtain coherent data about stormwater runoff which will be helpful to plan, design and manage urban stormwater.

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129. *Nõuded suplusveele ja supelrannale* [*Requirements to Bathing Water and Beach*]. Regulation of the Government of Estonia No. 74. Adopted 03.04.2008, 2008. Available from: https://www.riigiteataja.ee/akt/129082011006 [accessed 10 November 2015].
130. EU. Directive 2006/7/EC of the European Parliament and the Council of 15 February 2006 concerning the management of bathing water quality and repealing. Directive 76/160/EEC2006. *Official Journal of the European Union*, 2006, L64, 37–51. Available from: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32006L0007 [accessed 25 August 2015].

Linnade sademevee tõhusama seire, parema planeerimise ja juhtimise suunas

Bharat Maharjan, Karin Pachel ja Enn Loigu

Sademevee andmete ebapiisavast kättesaadavusest tingitud vähene teave ei võimalda hinnata saasteainete tegelikke kontsentratsioone ja koormusi. Sellises olukorras on keeruline teha pädevaid otsuseid jätkusuutliku planeerimise, projekteerimise ja poliitika kujundamisel, samuti kavandada sademevee äravoolu ning saasteainete vähendamiseks sademeveesüsteeme, sh alternatiivseid keskkonnasõbralikke lahendusi.

Usaldusväärsete ja esinduslike andmete saamiseks on oluline lähtuda standardiseeritud seireprogrammist ning proovivõtu- ja analüüsiprotseduuridest. Seireprogramm peab olema optimaalne ja tõhus ning samal ajal arvestama proovivõtu ja analüüsimise maksumust ning tehnilisi raskusi.

Uurimuses on antud ülevaade teadusartiklites sagedamini mainitud seireprogrammide ja proovivõtuviiside tõhususest. Tõenäolisi lähenemisviise koha valikule, seire parameetritele ja proovide kogumise süsteemile on võrreldud nende tõhususe, taskukohasuse ja rakendatavuse alusel. Selle teabe põhjal on Tallinna linna sademeveevalgalale pakutud sobivaim proovivõtuprogramm. Veelgi enam, uurimus annab otsusetegijatele võimaluse valida erinevate variantide seast sobivaim seireprogramm, mille rakendamine tagab sademevee kohta ühtsed võrreldavad andmed.

PAPER IV

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Modelling of runoff, quality and loads in the large urban catchment.

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Abstract. Identification of storm water runoff, pollution load and their contributing land use is essential in implementing stormwater management strategies. Hydrologic modelling provides the opportunity to assess them at limited data resources. In this study, storm water management model 'SWMM5' is applied for model development for the large basin in Tallinn. A geographic information system (GIS) tool is used for sub-catchment delineation, identification of directly connected impervious areas (DCIA) and preparation for catchment input parameters. The model is calibrated and verified using sampled storm events to estimate event mean concentrations (EMCs) and annual loads. The predictive capability for quantity is good and quality is moderate. The findings from the model show the imperviousness is lower at 19.7 % due to abundant pervious land cover. However, the impact of DCIA, in particular roads and roofs, have a relatively lower area, and this significantly impacts runoff production up to 75 % and loads up to 66 % (total phosphorus) and 71 % (total suspended solids). The first flush at the initial portion of runoff is less important for the small intensity of rainfall, but heavy rain and snowmelt possess substantial runoff and loads. When the grab sampling is applied, it should focus on the medium and large events within 6 hours of storm commencement in order to achieve better mass estimations.

Keywords. Hydrologic modelling, impervious area, event mean concentrations, mass loads, first flush.

1. Introduction

Stormwater runoff in several urbanised areas has induced flooding and degraded the receiving water bodies. Runoff reduction and the control of pollution loads to coastal sea areas has been a goal for the Baltic sea states for the past number of decades (*HELCOM, 2002*; *2007*) and it has been reflected in national strategies, acts and regulations such as, in Estonia, the Estonian Water Act (*RTI, 2015*), Tallinn stormwater strategy 2030 (*RTI, 2012*) and Tallinn city development plan (*RTI, 2013b*), among others. The estimation of actual stormwater quality and quantity has been a requirement in evaluating the compliance of stormwater management regulations and in implementing effective control measures, and it is an inherently difficult task when there is a lack of sufficient information (*Chiew & McMahon, 1999*; *Park & Stenstrom, 2008*). Though effective in determining it, extensive monitoring campaigns are not always feasible due to resource availability and associated uncertainties. In such a situation, stormwater modelling is a helpful tool that uses limited data resources and can simulate time intervals beyond the monitoring period (*Vezzaro & Mikkelsen, 2012*).

The constituents of stormwater runoff mostly depend on the rainfall and catchment characteristics (*Nazahiyah et al, 2007*; *Liu et al, 2012*; *Liu et al, 2013*) as well as on the upstream human activities (*Brezonik & Stadelmann, 2002*; *Park et al, 2009*). Models are primarily underpinned by rainfall (rainfall intensity, rainfall duration, antecedent dry condition) and catchment characteristics such as land use type and surface imperviousness (*Park et al, 2009*; *Liu et al, 2013*). However, it is also needed to consider the urban forms such as road layout and the spatial distribution of urban areas, which has a significant influences on pollutant generation (*Liu et al, 2012*; *Liu et al, 2013*). Moreover, mixed land use as present in large catchment basins produces a higher variability in stormwater quality, as there is a high interspersion of various land use types (*Lee et al, 2009*). Therefore, the large catchment behaves in a different way to small urban catchment in runoff and pollutant loading.

One of the important catchment characteristics is surface imperviousness. An increased proportion of surface imperviousness accelerates the runoff rate and produces shorter times of concentration or lag times as well as increased peak flow and runoff volume; however, the proximity of these impervious surfaces to drainage system plays a significant role in these interactions(*Shuster et al, 2005*). Estimation based on total impervious area overestimates quantity and quality of stormwater (*Shuster et al, 2005*; *Ebrahimian et al, 2016*) and the larger area of catchment is more crucial to add up the amount. Effective impervious area is used by many researches instead of total impervious area to effect closer results. DCIA needs to be accounted for effective impervious area (EIA) because the part that is not directly connected to storm drainage has less impact on output (*Lee & Heaney, 2003*; *Ebrahimian et al, 2016*). Identification of the potential DCIA is essential in implementing the possible solution for reducing runoff and pollution load.

The review on the stormwater models by Elliott and Trowsdale (*Elliott & Trowsdale, 2007*) and Jayasooriya and Ng (*Jayasooriya & Ng, 2014*) found that EPA Storm Water Management Model (SWMM) has a more effective performance in simulating stormwater quality and quantity. It is a widely used water quality model that has the capacity for both single-event and continuous simulation in the prediction of flows and pollutant concentrations. Many studies have indicated that SWMM has reasonable accuracy when the model outcomes are calibrated and validated (*Jayasooriya & Ng, 2014*). There is broad applicability of SWMM for simulating runoff and quality dynamics: hydrology assessment for pre/post development condition (*Jang et al, 2007*), pollutant wash-off water quality analyses (*Tsihrintzis & Hamid, 1998*; *Temprano et al, 2006*; *Lee et al, 2010*), combined sewer overflow modelling and assessment (*Zhang & Li, 2015*), flood forecasting (*Han et al, 2014*), and stormwater treatment facilities modelling and assessment (*Burszta-Adamiak & Mrowiec, 2013*; *Guoshun et al, 2013*).

Many studies applied the model for assessing runoff and loads with calibration and verification (*Tsihrintzis & Hamid, 1998*; *Temprano et al, 2006*; *Nazahiyah et al, 2007*; *Tan et al, 2008*; *Lee et al, 2010*; *Chow et al, 2012*; *Mancipe-Munoz et al, 2014*; *Rosa et al, 2015*). They are mostly for small catchment basins. Tan et al. (*2008*) and Mancipe-Munoz et al. (*2014*) worked on comparatively large urban catchments but mainly focused on runoff calibration, though they worked for continuous events too. There are few studies on quality dynamics for the large catchment basins. In Estonia, the modelling of stormwater is rarely found. Hood et al. (*2007*) used SWMM model to estimate flow and pollution load of a moderate size in the Tallinn subcatchment, but they have not well evaluated predictive capabilities. The small six subcatchments with distinctive land use (transportation, residential and commercial) in Tallinn were analysed for runoff and suspended solids by Koppel et al. (*2014*). The runoff dynamics of mixed land use can be different from single land use and can provide a resultant runoff coefficient that is different from individual land use (*Lee et al, 2009*). The studies by Hood et al. (*2007*) and Koppel et al. (*2014*) used the rainfall data from Harku station, which is almost 5−7 km far from the studied sites. As no other stations nearer the sites were available at that time, the analysis using distant stations can lead to unconvincing results. There is also room to look at the impact of directly connected impervious areas. Lee and Heaney (*2003*) modelled the hydrologic performance of DCIA and reported that DCIA is the main contributing area of runoff and has the most pronounced effect on urban hydrology. DCIA or the connectivity to the urban area at the catchment scale influences the hydrologic response (*Yang et al, 2011*; *Burns et al, 2015*).

This study is mainly focused on model development for the Mustoja basin in Tallinn. It aims to identify the sensitive input parameters and potential DCIA that influence runoff and loads in the large catchment basin. It will estimate EMCs and mass loads and finally use these results to evaluate the practiced sampling campaigns.

2. Material and method

Study catchment area description

The study is conducted in the Mustoja basin, the large catchment basin of Tallinn city (Fig.1). Tallinn is the capital of Estonia and where approximately 32 % of population is centred. It is in the northeastern part of Europe on the shores of the Gulf of Finland. It has a humid continental climate with warm to mild hot summers and cold snowy winters. Normally, average monthly temperature ranges from -5.7 °C in February to 16.3 °C in July (*EWS, 2015*). Total annual rainfall in Tallinn is 704 mm and average monthly rainfall varies from 32 mm in April to 86 mm in August. Snow cover usually lasts from mid-December to late March. The study catchment comprises approximately 10.24 km^2 (30 % of the Tallinn area), which mainly spreads over the Kristiine and Mustamäe districts in the upstream side. Runoff mainly flows through underground pipe networks and ditches to the downstream natural channel where three pipes under Marja, Haabersti and Mustjõe streets intersect. Finally, this water is discharged to Kopli beach and the Baltic Sea. The land use within the catchment is mainly residential covered with private and apartment buildings in the upstream side. Industrial and commercial areas are dominant features in the downstream side within the catchment.

In this study, EPA SWMM version 5.1 (SWMM5) was used to simulate stormwater quantity and quality. It is a comprehensive hydrological and water quality model used for single event or long term events in urban areas (*Rossman, 2010*). SWMM is common throughout the world for planning, analysis and design related to stormwater drainage systems in urban areas. EPA provides this model and related graphical user interface free of charge. The SWMM conceptual model comprises four major environmental compartments: (i) the atmosphere compartment e.g. rain gauge objects, accounts for precipitation and pollutants from air; (ii) the land surface compartment, which is represented through subcatchment objects, models areas that receive precipitation and generate runoff; (iii) the ground-water compartment e.g. aquifer objects, receives infiltration from the land surface and provides input to the transport compartment; and (iv) the transport compartment, routes flow from runoff source areas through a network of pipes, channels, etc. (*Rossman, 2010*). SWMM offers a selection of three different built-in infiltration models and flow routing methods. The infiltration loss on pervious area was estimated using Horton's equation (*Horton, 1933*) and the runoff transport is computed using the dynamic wave routing method under the complete Saint-Venant equations that considers the back water effects with 30 second time steps.

Fig.1. Study site, Mustoja catchment basin in Tallinn

Model development

Model development can be divided into two steps. In the first step, runoff modelling is prepared, which requires the information of catchment characteristics, conveyance system, rainfall and infiltration. And in the second step, the quality model is prepared using the runoff model, which requires build-up and wash-off components.

Catchment characteristics are catchment area (A), catchment width (W), average slope (S_o), impervious percentage (% imp), surface depression storage and surface roughness. Surface depression storage includes impervious (D_{imp}) and pervious depression storage (D_{per}) while surface roughness includes impervious (N_{imp}) and pervious surface roughness (N_{per}). Subcatchments were delineated using the drainage networks and surface slope. The drainage network was provided by AS Tallinna Vesi in digital format, which includes the location/elevation of stormwater pipes and manholes, pipe diameter, pipe material and year constructed (Table 1). Mustoja catchment basin is mainly served with a separate storm drainage system of approximately 51 km of pipes with diameter varying from 0.15 to 2 m and 4 km of drain ditches constructed within 79 years. Surface slope was determined using a 1-m resolution digital elevation map (DEM) provided by Estonian Land Board. A GIS toolbox was used to prepare the catchment properties. Mustoja basin was divided into 378 subcatchments (see in Fig.1) ranging in size 0.06-23.8 ha with slope varying 0–11.1 %. The width of each catchment was computed from the longest flow path method within the catchment and it ranged 25.8–3002.8 m.

In estimating impervious percentage, the land use map was obtained from the Estonian Land Board for the year 2014. According to Estonian National Topographic Database (ENTD), Mustoja basin had impervious surfaces of almost 50 %, most of which are roads, the fields of production sites and buildings (Table 3). Pervious surfaces were mainly formed by the green area with a quarter and by forest and private yards with 1/5 of the catchment area. Total impervious area (TIA) does not contribute to the actual urban runoff. Instead, EIA or the portion of TIA that is hydraulically connected to the storm sewer system, is an important parameter in determining this runoff (*Lee & Heaney, 2003*; *Ebrahimian et al, 2016*). Directly connected impervious areas (DCIA) were identified and separated from the non connected parts following the procedure explained in the paper by Lee and Heaney (*2003*). Field investigation, areal maps, online maps and storm pipe details were used, and imperviousness was spatially analysed using geographic information systems. Numerous land uses are grouped together into simple classification as residential, commercial, industrial, forest, water bodies, roads and roofs as in Table 3. Roads and roofs are potential urban land uses for runoff and pollutants (*Ballo et al, 2009*). Approximately, 55.7 %, 7 %, 10.2 %, 23 %, 3.9 % and 0.2 % areas were determined as residential (R), industrial (I), roads (Rd), residential roofs (Rr), commercial roofs (Cr), forest and water respectively (Table 3). DCIA was found to be nearly 27 % (278 ha) of which TIA was 79 % (217 ha) that reduced to EIA of 57 % (156 ha). EIA was estimated because all the runoff does not enter the inlets despite the fact that DCIA only represents the land use connected to the drainage system. Nevertheless, when the DNCIA (directly not connected impervious area) not connected to drainage system was considered, TIA was 44 % (448.9 ha) and EIA was 19 % (198.4 ha). The major EIA was DCIA roads, followed by DCIA commercial roof, industrial areas and residential areas.

Table 1. Pipe network details in Mustoja catchment basin

Diameter (m)	pipes	Length (m)	Installed year	Typical installed year	Typical material
0.1-3.0	124	3,335.2	1966-2015	2008/1968	PP, ABS
3.0-5.0	652	18,941.3	1956-2015	2008/1978/1972	ABS, PP, PVC, concrete
5.0-7.0	544	17,319.4	1936-2015	1968/1978	concrete
7.0-9.0	50	1,506.9	1956-2005	1968/1965	concrete
9.0-1.5	197	7,295.1	1956-2005	2003/1972/2000/1967	concrete
1.5-2.0	41	1,852.1	1966-2005	1974/1998/1972	concrete
Grand Total	1608	50250.0	79		

PP: Poly Propylene; ABS: Asbestos; PVC: Poly Vinyl Chloride

Table 2. Land use details within the catchment

Land use (LU)	Area (ha)	% LU
Pervious	***512.4***	***50.0***
pond	0.2	0.0
stagnant water body - unknown	1.7	0.2
forest	39.0	3.8
shrubbery	0.8	0.1
cellar	0.0	0.0
green area	251.0	24.5
other open area	60.3	5.9
private yard	159.4	15.6
Impervious	***511.5***	***50.0***
ruins	0.5	0.1
horticultural land	1.5	0.2
field of production	104.2	10.2
greenhouse	4.0	0.4
basement	0.2	0.0
building under construction	0.0	0.0
other facility	0.5	0.0
road	235.3	23.0
building	99.4	9.7
garage	8.8	0.9
manufacturing building	54.2	5.3
shelter	2.5	0.2
bridge	0.3	0.0
Grand Total	**1024.0**	**100.0**

Table 3. Simplified land use classified into DCIA and DNCIA of TIA and EIA

Simplified Land use (LU)	Area (ha)	Total % LU	TIA (ha)	EIA (ha)	Land use details
DCIA					
Commercial Roof	55.9	5.5	50.3	33.8	commercial building, manufacturing building
Industrial	32.9	3.2	14.0	17.6	field of production
Residential Roof	38.6	3.8	34.7	10.4	building under construction, commercial building, private building, shelter
Road	147.5	14.4	118.0	94.2	bridge, roads (road as drain, DCIA road, feeder road, one side vegetated street)
Total	*274.8*	*26.8*	*217.0*	*156.0*	
DNCIA					
Commercial Roof	13.6	1.3	12.2	1.4	DNCIA manufacturing building
Industrial	71.3	7.0	26.4	3.6	field of production
Mixed Residential & Commercial	4.5	0.4	2.1	1.4	residential and commercial building
Residential	481.8	47.1	75.3	24.7	basement, cellar, garage, green area, horticulture land, other open area, private yard, Private yard, ruins
Residential Roof	48.1	4.7	43.3	4.8	DNCIA building, manufacturing building
Road	88.1	8.6	70.5	6.1	side vegetated street , road (road along with swale, road along with swale channel)
Forest	39.8	3.9	2.0	0.4	forest, shrubbery
Water	1.9	0.2	0.0	0.0	pond, stagnant water body - unknown
Total	*749.2*	*73.2*	*231.9*	*42.4*	

DCIA: Directly connected impervious area; DNCIA: Directly not connected impervious area

Rainfall details

Stormwater runoff estimation in the Tallinn region was usually based on the Tallinn-Harku station, about 6 km from the pilot basin, where the meteorological observations started in 1805. The rainfall varies with time, space and altitude among stations even within the catchment. Rainfall measuring equipment must be close to or within the catchment in order to take account of the climatic factors, characterisation and modelling of the stormwater drainage system in a statistically reliable way (*Löwe et al, 2014*). After 2013, AS Tallinna Vesi installed 9 other rainfall measuring stations. Within the Mustoja basin, on the downstream area near Saarma street, the department of Environmental Engineering of Tallinn University of Technology installed a tipping bucket rain gauge "Saarma" in May 2014. When applying the Thiessen polygon method (*Fetter, 2001*) using a GIS toolbox, the influential stations were identified as "Tondi 90" and "Saarma" (see in Fig.1). The Tondi 90 station was also within the basin and in the upstream area near Tondi street. One minute rainfall data from these two stations were used for the simulation so that the stations close to the subcatchments could feed them the corresponding rainfall. The average monthly temperature (in Harku station) and rainfalls recorded in three stations (Tondi 90, Saarma and Harku) during Jan 2014 to Feb 2016 are presented in Fig. 2. August 2014 and July 2015 were the wettest months while February to April were dry months in 2014 and 2015. Besides these, October 2015 was the driest month. Compared with the normal rainfall pattern in Harku station (1981−2010) (*EWS, 2015*), these two years were dry years with approx. 34 % and 26 % less rain in 2014 and 2015 respectively.

The storm events recorded from May 2014 to Dec 2015 in the Tondi 90 and Saarma stations were similar in rainfall characteristics (Table 4). Over 2015, 144 to 156 events occurred with average rainfall intensity 0.1 to 4.8 mm/hr, producing 523 to 550 mm of rainfall. When the intensities were averaged over the years, the intensity amounted to 0.5 to 0.7 mm/hr. Most of the storms (90 %) during these two years were below 1.4 mm/hr. An extreme event during the record period reached the peak of 19.4 mm/hr on 22 Aug 2014. Average total event rains were small in range, 1.7− 2.2 mm for a duration of 6.1−8.1 hrs and inter-event time of 52.8−59.8 hrs.

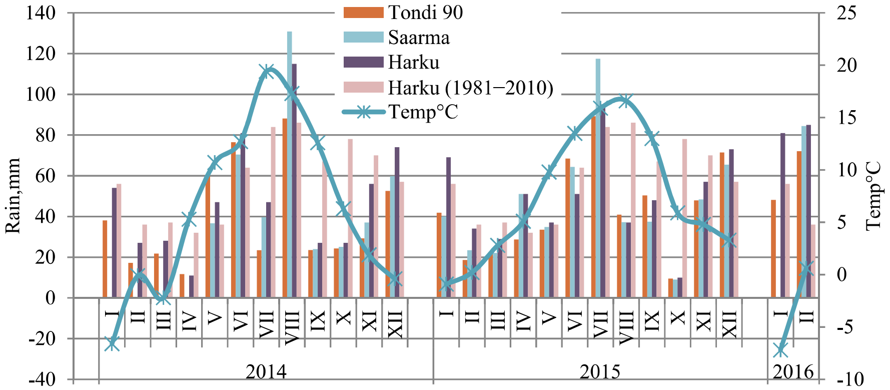

Fig. 2. Monthly temperature, monthly rainfalls in three rain gauge stations and long-term average rain.

Table 4. Rainfall characteristics in 2014 and 2015

Station (months)	**Year**	**No. of events**	**total rain (mm)**	**Mean Rainfall Intensity (mm/hr) [Range] mean, median, 0.9 percentile**	**Peak (mm/hr) [Range] mean**	**Total Event Rain (mm) [Range] mean**	**Duration (hrs) [Range] mean**	**Inter-Event Time (hrs) [Range] mean**
Tondi (V−XII)	2014	107	363.4	[0.1–4.65] 0.6, 0.4, 1.3	[0.1–7.1] 1.3	[0.05–10.25] 1.7	[0.5–45.5] 7	[5.75–328] 52.8
Saarma (V−XII)	2014	98	423.2	[0.2–18.8] 1, 0.5, 1.4	[0.2–19.4] 1.9	[0.1–14] 2.2	[0.5–52.5] 6.5	[5.75–313.5] 57.7
Tondi (I−XII)	2015	156	522.7	[0.1–5.3] 0.5, 0.3, 1.1	[0.1–10.3] 1.1	[0.05–17.1] 1.7	[0.5–60.5] 8.1	[8.5–558.5] 55.2
Saarma (I−XII)	2015	144	549.6	[0.2–4.8] 0.7, 0.4, 1.3	[0.2–16.4] 1.3	[0.1–15.7] 1.9	[0.5–54.5] 7.7	[10–352.5] 59.8

Storm events and sampling details

Three storm events were used for the model calibration and four events for validation. The calibrated events were during 9 September 2014 (event 1), 22−23 September 2014 (event 2) and 4−5 December 2015 (event 3). The rainfall characteristics (intensity, duration, antecedent dry days and total rain) during these events are presented in Table 5. Event 1 and Event 2 were captured after a long dry period of 12.1 and 12.6 days, one had intense rain with 2.2 mm/hr of rain for a short duration (2.3 hrs) and another had medium rain with 0.8 mm/hr for a long duration (26 hrs). Event 3 was recorded during wet weather conditions with antecedent dry days (ADD) of 1.5 days and was below 1.4 mm/hr; this falls between the medium and 90 percentile across all recorded years. Event 1 did not have quality data; therefore, it was used only for runoff calibration.

Automatic flow measurement unit was installed by AS Tallinna Vesi and this provided flow rate for each 10 min for event 1 and event 2. At the same time, TUT installed a water level measurement gauge to form a discharge-rating curve. The time interval sampling approach named as sampling approach 1(SA1) was used to collect samples during the events. Grab samples were also taken two times a week and a total of 104 samples were taken during the period from 6/11/2014 to 16/12/2015, which is called the random sampling approach or sampling approach 2 (SA2). On each occasion, the flow was measured using a flow tracker along with instantaneous water level. Samples were analysed by competent water quality laboratories certified by the Estonian Accreditation Centre (Eesti Akrediteerimiskeskus, EAK) that followed standard EVSEN ISO / IEC 17025 consistently. Many parameters e.g.

temperature, dissolved oxygen, conductivity, pH, BOD, total suspended solids (TSS), ammonia, total nitrogen (TN), total phosphorus (TP), chloride, oils, microbiological parameters and heavy metals were measured. Heavy metal samples were taken every week, and a total of 30 samples were determined for analysing the content of Cd, Cr, Cu, Pb, Ni, Fe and Zn. In this study, TSS and TP parameters with a strong linear relationship (regression coefficient 0.72−0.86) were simulated and the Water Quality Laboratory in Tallinn University of Technology was involved in analysing these parameters.

Table 5. Sampled storm event characteristics

Events	Antecedent dry days	Duration (hrs)	Mean Rainfall Intensity (mm/hr)	Peak (mm/hr)	Total Event Rainfall (mm)	rainfall intensity (mm/day)
Event 1 (9 Sep 2014)	12.1	2.3	2.2	8.7	5.1	4.3
Event 2 (22–23 Sep 2014)	12.6	26.0	0.8	3.3	6.2	4.3
Event 3 (4–5 Dec 2015)	1.5	13.5	1.2	3.1	9.7	7.6

Other input parameters for catchment properties were adopted from the range provided in SWMM User's manual (*Huber et al, 1988*), books (*Bedient & Huber, 1988*; *Wanielista, 1990*) and published papers (*Temprano et al, 2006*; *Nazahiyah et al, 2007*), e.g. 0.3 mm for D_{imp}, 2.5 mm for D_{per}, 25 % for zero depression storage, 0.01 for surface roughness coefficient for overland flow on impervious portion, 0.3 for surface roughness coefficient for overland flow on pervious portion, etc. (Table 9). The infiltration parameters (maximum infiltration rate, minimum infiltration rate and decay constant) were often difficult to identify and adopted from the range provided by Bedient and Huber (*1988*) and Nazahiyah et al. (*2007*) based on the soil type used. Pollutant build-up depends on the land use, dirt and dust accumulation and ADD, whereas pollutant wash off depends on land use, runoff rate and removal efficiencies. The build-up and wash-off parameters provided by Chow et al (*2012*) for different land uses were similar to the values used by Koppel et al. (*2014*) in the local context and those values were adopted to the associated land use types.

Sensitivity and model performance test

The robustness of the results from the model were analysed for sensitivity varying the values of the input parameters. For example, % imp and width were changed within ±10 % and other parameters within the range as presented in Table 9. Sensitivity coefficient (Sc) was the indicator for this analysis and this measures the effect of change in one factor to another (*James & Burges, 1982*; *Chow et al, 2012*). The model goodness of fit was tested with four types of indicators as used by Chow et al. (*2012*) and Koppel et al. (*2014*): correlation coefficient, relative error (RE), normalised objective function (NOF) and Nash-Sutcliffe coefficient (NSC). Correlation coefficient (CC) is a general statistical measure of the linear relationship between observed and predicted values. Generally, the best calibration requires CC to be as close to 1 as possible. Relative error (RE) (*Chow et al, 2012*) for flow and peak flow measures the average tendency of the simulated data to be larger or smaller than observed. The optimal value of RE is 0.0, but within ±10 % can be acceptable with low magnitude values indicating accurate model simulation. If O is the observed value, S is simulated value, O_i is i^th^ observed and S_i is i^th^ simulated value, n is the total number of observations, then, RE is calculated as follows.

$$RE = \frac{S-O}{O} * 100 \qquad 1$$

Normalised objective function (NOF) is root mean square deviation (RMSD) normalised with the mean of the observed values. Optimal value is 0 but 0 to 1 can be acceptable for calibration (*Kornecki et al, 1999*). It is expressed as follows:

$$\boldsymbol{NOF = \frac{RMSD}{\bar{O}} = \frac{\sqrt{\sum_{i=1}^{n}\frac{1}{n}(S_i - O_i)^2}}{\bar{O}}} \qquad 2$$

The NSC was calculated by formula in Eq. (3) (*Nash & Sutcliffe, 1970*). NSC ranges between 0 and 1.0, with NSC = 1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance.

$$\boldsymbol{NSC = 1 - \frac{\sum_{i=0}^{n}(O_i - S_i)^2}{\sum_{i=0}^{n}(O_i - \bar{O})^2}} \qquad 3$$

3. Result and Discussion

Sensitivity Analysis result

In the studied basin, the sensitive input parameters were found to be % imp, width (W), D_{imp} and N_{imp} (Table 6). Among them, % imp has a significant influence on runoff flow rate at sensitivity coefficient (Sc) = 0.82 and peak flow at Sc = 0.68. Catchment width has moderate influence with Sc of 0.44 for flow rate and 0.36 for peak flow. Both D_{imp} and N_{imp} have a negative coefficient, which indicates that the output values will increase with a decrease in these input parameters. In this large basin, they are not highly significant standing at the range -0.019 to -0.029 for D_{imp} and -0.008 to 0.018 for N_{imp}. However, D_{imp} is comparatively more influential for initial peak flow, having Sc of -0.029, which indicates that the depression storages regulate the first peak in hydrograph. Tan et al. (*2008*) and Chow et al.(*2012*) found a similar influence for % imp. However, the width of their subcatchments was more sensitive on peak flow than runoff depth, which is not the same case in this study. Instead, there is nearly an equal influence on both peak flow and flow rate. Unlike their study, the basin is large and the sensitivity due to width and N_{imp} on peak flow is not strong.

Table 6. Sensitivity Coefficient for input parameters.

Parameters	Sensitivity coefficient		
	Runoff volume	**Runoff flow rate**	**Peak flow**
% Imp factor	0.610	0.816	0.687
W factor	0.309	0.439	0.357
D_{imp}	-0.029	-0.019	-0.029
D_{per}	0.000	0.000	0.000
N_{imp}	-0.001	-0.018	-0.008
D_{per}	0.000	0.000	0.000

Calibration and verification results

The model is evaluated for the predictive capabilities through four indicators using equations 1 to 3. The result in Table 7 and Table 8 shows the correlation coefficient, NOC and NSC are within the acceptable range for runoff quantity for all events, indicating the modelled and measured runoff are in a good relationship. The model for runoff simulation is acceptable at three important indicators CC, NOF and NSC, as CC is 0.87−1 i.e. close to 1, NOF is 0.1− 0.3 i.e. between 0 to 1 and NSC is 0.3–1 i.e. close to 1, though RE beyond ±10 % at flow error less than 20 % and peak error between -27.4 to +21.2 %. Similarly, the indicators like correlation coefficient and NOC for quality simulation (in Table 8) suggest that the predictive capability of the model is in an acceptable range standing at the range 0.4−1 for CC and 0.1−0.5 for NOC. However, NSC and RE are not in a good range. NSC for TSS is poor but it is good for TP at 0.4− 0.7, while RE for both quality parameters can go beyond the acceptable range. Overall, the model is acceptable for runoff quantity, but it provides less accurate estimation for quality performance. Calibration through increasing a number of events can reduce the error to some extent.

The calibrated results for runoff are presented in Table 9 and for quality in Table 10. These are the best-fit values for the input parameters after testing the goodness of fit. The % imp found at 0.9 factor (Table 9) after calibration is 19.7 % where the runoff coefficients for different land use varies as R: 0.05 to 0.2, Rr: 0.15 to 0.20, RC: 0.2 to 0.26, I: 0.09 to 0.45, Cr: 0 to 0.56 and Rd: 0.03 to 0.57, depending on the proximity of the connection to the drainage system. Temprano et al. (*2006*) in residential areas of Spain and Hood et al. (*2007*) in the highly residential Tallinn area found rather lower impervious percentages of 15.9 % and 7.2 % respectively. A relatively large pervious area within the subcatchments and the effect of mixed land use have resulted in lower imperviousness. The depression storage used in this model is the average of dry and wet weather, which is determined as 0.7 mm for the basin. It is higher than the values obtained by Hood et al.(*2007*) and Koppel et al. (*2014*), where they proposed 0.15 to 0.29 mm for the Tallinn area. Depression storage for impervious area is sensitive for initial peak flow, and it varies from 0.3 to 1 in this study depending on the weather conditions. Chow et al. (*2012*) provided this storage for residential 0.2 in wet weather and 0.8 in dry weather, while it can increase to 0.75 in wet and 1.05 in dry conditions for commercial area. Temprano et al. (*2006*) for residential is rather higher at 2.5 mm. Therefore, the value obtained for this basin can be justified. Manning's roughness for impervious area is 0.0135, since the impervious surface characteristics within this area are concrete/asphalt paving and/or a gravelled surface (*Huber et al, 1988*). A similar value is also used by Koppel et al. (*2014*) and Chow et al. (*2012*) in their studies.

Table 7. Goodness of fit runoff quantity simulation

Goodness of fit Indicators	Acceptable range	Event 1		Event 2		Event 3	
		Flow rate	Peak flow	Flow rate	Peak flow	Flow rate	Peak flow
CC	close to 1	0.98	NA	0.87	0.99	0.94	1.00
RE %	±10%	4.1	-27.4	5.6	0.6	19.4	21.2
NOF	0 to 1	0.3	0.3	0.2	0.1	0.3	0.2
NSC	close to 1	1.0	NA	0.6	0.8	0.7	0.3

Table 8. Goodness of fit for quality simulation

Goodness of fit Indicators	Acceptable range	Event 2		Event 3		Event 2		Event 3	
		TSS	Peak TSS	TSS	Peak TSS	TP	Peak TP	TP	Peak TP
CC	close to 1	0.8	0.8	0.4	-1.0	0.9	1.0	0.9	0.9
RE %	±10%	-1.12	-14.5	4.3	-13.4	-33.0	-15.6	11.0	-7.9
NOF	0 to 1	0.4	0.3	0.3	0.3	0.5	0.2	0.2	0.1
NSC	close to 1	0.7	-48.8	-0.5	-1.0	0.4	0.4	0.7	0.5

Table 9. Calibrated values of input parameters for simulating runoff quantity

Parameters	Range (Reference)	Calibrated values
% Imp factor	±10 %	0.9
W factor	±10 %	1
D_{imp}	0.3 to 2.3 (*Huber et al, 1988*)	0.7
D_{per}	2.5 to 5.1 (*Huber et al, 1988*)	3
N_{imp}	0.01 to 0.03 (*Wanielista et al, 1997*)	0.0135
N_{per}	0.02 to 0.45 (*Huber et al, 1988*)	0.2
Maximum Infiltration, mm/hr	50 to 200 (*Bedient & Huber, 1988*)	50
Minimum Infiltration, mm/hr	0.5 to 12 (*Nazahiyah et al, 2007*)	0.5
decay constant, L/hr	0.000389 to 0.0039 L/s i.e. 1.4 to 14 L/hr (*Nazahiyah et al, 2007*)	4

Build up and wash-off parameters determine the amount of pollutant discharged to drains. The more impervious the area, the more wash-off coefficients were found. Build up is slightly higher in commercial area than residential and industrial has slightly higher than commercial area (Table 10). The analysis is different in the aspect of land use separation from other previous studies listed in Table 10. In this study, roads and roofs were separated to investigate their effect on build-up and wash-off components. Wash-off coefficients for DCIA roads and roofs are higher than DNCIA, which indicate that they are crucial for pollutant load. Maximum build ups (build up coefficients) are relatively small compared to findings by Temprano et al. (*2006*) and Hood et al. (*2007*) and the model fits values similar to the findings of Chow et al. (*2012*), suggesting that there are cleaning activities on the basin upstream. Street cleaning is active in the basin as it is one of the action plans of the stormwater strategy in Tallinn (*RTI, 2012*). In the model, the cleaning efficiency used is 30 to 50 % for TSS and up to 90 % for TP in DCIA roads at an interval of 7 to 14 days.

Table 10. Calibrated build-up and wash-off input parameters

Land use	TP				TSS			
	Build up Coeff	Build up Exponent	Wash off Coeff	Wash off Exponent	Build up Coeff	Build up Exponent	Wash off Coeff	Wash off Exponent
This study								
R	0.2	0.02	0.2	0.7	3	0.8	0.3	1.5
Mixed R and C	0.2	0.03	0.3	1	3	0.75	0.3	1.2
I	0.25	0.016	0.5	1.2	10	0.7	0.5	1.5
R Roof								
[DCIA, DNCIA]	[0.2, 0.2]	[0.03, 0.02]	[0.2, 0.2]	[0.8, 1.4]	[3, 3]	[0.8, 0.8]	[0.25, 0.2]	[1.5, 1.5]
C Roof								
[DCIA, DNCIA]	[0.2, 0.2]	[0.03, 0.03]	[0.5, 0.2]	[1.2, 1.2]	[10, 10]	[0.8, 0.8]	[0.6, 0.2]	[1.5, 1.5]
Road								
[DCIA, DNCIA]	[0.4, 0.3]	[0.08, 0.04]	[0.5, 0.2]	[0.7, 1.2]	[10, 10]	[0.8, 0.8]	[0.6, 0.2]	[1.5, 1.5]
Other studies								
Temprano et al. (2006), Spain- R	46	0.3	0.13	1.2	46	0.3	0.13	1.2
Hood et al. (2007), Estonia - Mixed urban	0.25	0.0025	500	2.35	25	1	4.9	1.57
Chow et al. (2012), Malaysia [R, C, I]	[0.3, 0.5, 0.3]	[0.05, 0.1, 0.16]	[0.41, 0.4, 0.8]	[1.46, 1, 1.08]	[3, 13, 15]	[0.8, 0.8, 0.7]	[0.2,1.4, 3]	[1.4, 0.9, 0.6]
Koppel et al. (2014) Estonia- C and road						0.2		1

Table 11. Verification of quantity quality performance

Rain (mm)	Events	Verification Parameter	Observed	Simulated	RE %	Observed	simulated	RE %
			Volume (10^3 ltr)			Peak flow (LPS)		
21.07	08/06/2014	Runoff	7443.9	6999.1	6.0	910.0	839.3	7.8
43	06/11/2014	Runoff	12597.7	13372.2	-6.1	736.7	761.3	-3.3
53.4	21/05/2015	Runoff	17031.1	17612.1	-3.4	807.0	888.6	-10.1
12.4	06/08/2015	Runoff	6118.2	6705.4	-9.6	230.1	255.4	-11.0
			load (kg)			Peak flow (mg/l)		
12.4	06/08/2015	TSS	273.54	246.92	9.7	111.5	83.4	25.2
12.4	06/08/2015	TP	1.540	2.376	-54.3	0.5	0.8	-41.5

The four storm events: 08/06/2014, 06/11/2014, 21/05/2015 and 06/08/2015 were used for model verification. Evaluation was performed by comparing observed/simulated runoff volume and peak flow for quantity and observed/simulated event load and peak load for TSS and TP using their relative RE (

Table 11). The storm events for this verification have few observations and are not suitable for use with other indicators. A single event of 06/0/2015 was recorded to verify the quality performance. RE% for volume is between ± 10 % in a range of -9.6 to 6 % and peak flow is nearly ± 10 % in a range of -11.0 % to 7.8 %, indicating that the model can sufficiently predict stormwater runoff. However, the quality prediction is moderate for TSS and weak for TP having RE% beyond ± 10 %. Therefore, the verification results also suggest that it needs more events of quality observations to calibrate and verify the quality performance. Leecaster et al.(*2002*) proposed 7 storms or ~50% of the storms to get annual concentration within 10% uncertainty where as Bertrand-Krajewski (*2007*) recommended at least 10 storms to calibrate regression models with smaller confidence interval. The higher the number of storms if captured and calibrated, the lesser the model error can be expected.

Stormwater pollution load- TSS and TP output

The simulated event based concentrations and loads are presented in Table 12 and in Fig. 3. For the three events, EMCs for TSS are 33.6, 50.3 and 69.1 mg/l; EMCs for TP are 0.5, 0.5 and 0.7 mg/l; and mean runoff are 229.8, 187.6 and 422.6 l/s. The total volume of runoff is 16.0 to 20.0 million litres (ML). EMCs of TSS in event 2 and event 3 exceed the national stormwater limiting value of 40 mg/l (*RTI, 2013a*). The literature review by Göbel et al. (*Göbel et al, 2007*) showed EMCs variation is large and depends on urban forms or land uses. TSSs in their study were in the range of 0.2 to 937 mg/l where roofs (13−120 mg/l) and high-density traffic areas (99−937 mg/l) have high TSS discharges. TPs were in the range of 0.01 to 0.5 mg/l, where the range of 0.06− 0.5 mg/l was from roofs and 0.23−0.34 mg/l from traffic areas. In the city of Poland, the study in five small catchments with a total size of 116 hectares showed that the concentration of suspended solids varied in the range of 1.8 to 736 mg / l (mean ~31 mg/l) (*Barałkiewicz et al, 2014*). Compared to Estonian regulations, TPs in this study were below the national stormwater limit value of 1 mg/l (*RTI, 2013a*) and in poor status of river quality levels being greater than class IV limit (i.e. 0.1 mg/l in annex 4, Regulation No. 59)(*RTI, 2010*). The study of three stormwater catchments in Paris resulted in the total phosphorus content range of 0.3−3.52 mg/l (*Zgheib et al, 2012*) and in the Polish city, the total phosphorus content varied from 0.02 to 0.57 mg/l (mean ~ 0.17 mg / l) (*Barałkiewicz et al, 2014*). The EMC results of the Mustoja basin fell in the range provided by different studies, though TPs simulated are higher than the usual range. The illegal discharge of sewerage system can be suspected in the basin, which probably attributed to higher TPs. The peak concentrations were higher, ~3 to7 times the national TSS limits and 1.4 to 2.7 times the national TP limits.

The effect on runoff is observed for up to 19.7 hrs for event 1 where the single rainfall occurred. The baseflow in this event has a higher influence on increasing the volume of runoff (Fig. 3), approximately 67 % of total runoff. Therefore, the duration of runoff is crucial when estimating event total volume. The stormflow volume showed the increasing tendency proportional to total rainfall whereas stormflow mass load is likely to increase in proportion to rainfall intensity. In all three events, stormflow is more polluted than baseflow at nearly 90 % of total load for TSS and TP, which do not respond to the volume of runoff whether higher or lower than baseflow.

Table 12. Event based runoff and concentrations

Events	Rain (mm)	Runoff duration (hr)	Total Flow Volume (10^6 ltr)	Event flow		Event TSS loading		Event TP loading	
				Mean (LPS)	Peak (LPS)	EMC (mg/l)	Peak (mg/l)	EMC (mg/l)	Peak (mg/l)
Event 1	5.1	19.7	16.3	229.8	1,304.9	33.6	288.9	0.5	2.7
Event 2	6.2	23.7	16.0	187.6	452.1	50.3	170.9	0.5	1.2
Event 3	9.7	13.2	20.0	422.6	915.0	69.1	119.2	0.7	1.4

When simulating continuous rainfall for the years 2014 and 2015, the evaporation loss was also considered according to the daily average temperature obtained from Harku station. Water from the surface is continuously vaporised during the dry period. Annual evaporation was estimated as 0.6 ML (0.014 %) in both years. The annual outfall loadings are found to be 97.8 tons TSS, 1.5 tons TP from 4400 ML of runoff in 2014 and 110.7 tons TSS, 1.7 tons TP from 4500 ML of runoff in 2015 (Fig. 4). The simulated SWMM results are compared with the results from three monitoring programmes. The first one is the monitoring programme during 2012−2014 conducted by Tallinn University of Technology, the department of environmental engineering (TUT DEE) and AS Tallinna Vesi at the outlet of the Mustoja basin approximately 500m downstream from the studied outlet. This programme was commissioned by Tallinn Environmental Board and the samples were taken 6 times per year. The same methodology was continued in the second monitoring programme but it was conducted by the Estonian, Latvian & Lithuanian Environment (ELLE) Group in 2015. The third monitoring programme was SA2 conducted by TUT DEE, which was different in methodology in terms of sampling interval as the samples were taken twice a week. The total annual runoff was calculated based on daily average flow, and the total annual loads were calculated based on mean flow and mean concentration (Fig. 4).

In simulation, the system rainfall was the combination of rainfalls from the Tondi 90 and Saarma stations while TTU DEE , ELLE and SA2 used rainfall from Harku station (Fig. 4). System rainfall is relatively lower than Harku station by 25 % in 2014 and 11 % in 2015. However, the modelled runoffs exceed the TTU DEE and SA2 runoffs by some extent. It is nearly 10 % higher than TTU DEE in 2014 and 8 % lower than SA2 in 2015. On the contrary, ELLE runoff is significantly higher at 54 % than simulated runoff, although the annual rainfall is just 11 % higher.

One reason could be the method of calculation and another reason could be errors in measured values, which can make a difference in the annual runoff and loads. In the ELLE measurement, higher measured flow rates and concentrations have resulted the higher runoff and loads. ELLE TSS is enormously high at about 400 %. However, TSS from TTU DEE and SA2 are 35 % and 60 % lower than the SWMM results in 2014 and 2015. There are quite significant differences in TP loads at 60 % between TTU KTI and SWMM, at 59 % between SA2 and SWMM and 43 % between ELLE and SWMM. These deviations can be attributed to the load calculation method and further to the mean concentration and mean flow because the error in the means could magnify the estimates. Overall, the modelled runoff and loads are higher than estimations from TTU DEE and SA2, but they are significantly lower than ELLE measurements.

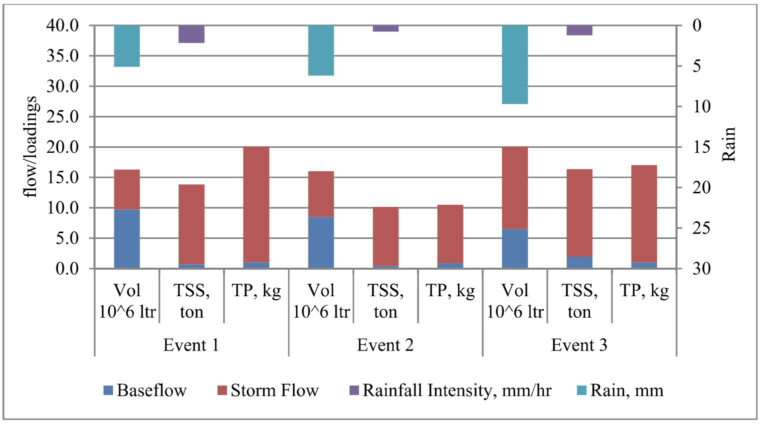

Fig. 3. Event based baseflow and stormflow loadings

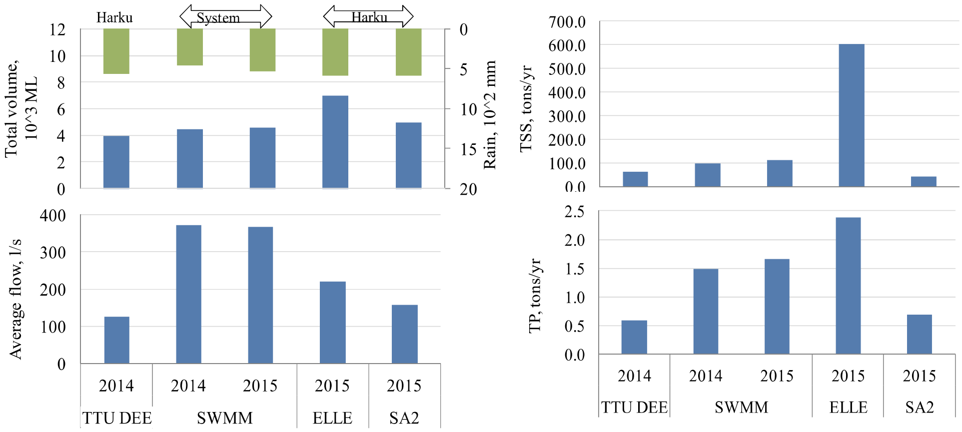

Fig. 4. Total annual runoff, average flow rate and total mass

Main contributing impervious surfaces

In the basin, the directly connected impervious area or DCIA was determined to be 26.8 % of the total land use area (from Table 3), but this amount of impervious area is found to be more effective for the runoff and quality output at 80.1 % for peak flow, 75.1 % for total runoff volume, 70.5 % for TSS and 66.1 % for TP (see in Table 13). The road area and commercial roof occupy nearly 77 % of the total effective impervious area. It shows that DCIA roads and roofs have a higher contribution to the runoff and pollution load, even though the overall runoff coefficient is found to be less at 0.18. Most of the areas are either pervious or not connected directly to storm drainage. This constitutes about 73.2 % of the total area.

Table 13. Contribution of DCIA on impervious land use

Events	Percentage	Max Flow (LPS)	Flow volume (10^6 ltr)	TSS (kg)	TP (kg)
Event 1	% DCIA/EIA	75.4	50.3	66.3	70.6
Event 2	% DCIA/EIA	83.7	89.8	72.8	47.6
Event 3	% DCIA/EIA	81.4	85.3	72.4	80.0
All Events	Average DCIA/EIA	80.1	75.1	70.5	66.1

DCIA: Directly connected impervious area, EIA: Effective impervious area

First flush Effect

It would be interesting to examine the first flush phenomenon in the basin if it exists, in order to control the initial contaminated portion through isolation or diverting the stormwater from the road or roof surfaces to the treatment facilities. The presence of the first flush phenomenon was assessed by plotting the cumulative fraction of the pollutant load against the cumulative fraction of the runoff volume (*Bertrand-Krajewski et al, 1998*) as in Fig. 5. The data above the diagonal line indicate higher loading during storm runoff, which suggests the presence of first flush (*Lee et al, 2004*). To account for the intensity of the first flush, the pollutant load swept along by the first 30 % of the volume was measured (*Temprano et al, 2006*; *Nazahiyah et al, 2007*). In the figure, four events (event 2 to event 5) including an additional event during the snow melt period (event 4: 26/01/2016 to 28/01/2016) and one immediately after the snow melt (event 5: 29/01/2016 to 01/02/2016) were used for TSS and TP. Event 2 and event 3 had no influence from snow melt, as the former had an antecedent dry condition of 12.6 days and the latter had an antecedent wet condition of ADD 1.5 days. The pollutant loadings are 38 %, 28 %, 50 % and 39 % of total TSS and 45 %, 36 %, 45 % and 33 % of total TP swept by 30 % of runoff volume in events 2, 3, 4 and 5, respectively. The degree of first flush for event 2 is not high, as it stands at 38 % for TSS and 45 % for TP, but the deviation from the diagonal line is clear after 40 % of runoff volume. It suggests that the flushing of the pollutant load is higher at a later stage within the last 60 % of runoff. ADD was almost 13 days for this event but the intensity of the rainfall played more than ADD, as a similar result is obtained for TP in event 2 but the deviation is less. The first flushes at initial portion of runoff for events 2, 3 and 5 are not significant. The maximum intensities of rainfall within the 30% of runoff for these events are identified as small sizes at 0.7 mm/hr, 1.7 mm/hr and 0.9 mm/hr. Instead, the latter part within the last 60 % of the volume is more important for the pollutant load. Similar findings were suggested by McCarthy (*2009*) where they found the first flush at the end of the event. Moreover, in relatively pervious area, Maestre & Pitt (*2005*) in their study didnot observed any first flush. However, Lee et al. (*2004*) suggested that a seasonal first flush can occur in most of the cases. Our study also showed the snowmelt event has a higher influence on the first flush at 50 % for TSS and 45 % for TP, indicating the effect of a seasonal first flush. Before event 4, there was an extensive period of minus temperatures, and pollutant was accumulated with the snow packing that was washed off after the temperature became positive during this event.

Comparison of loadings from four sampling approaches.

Finally, the sampling approaches are evaluated for the mass estimations, which provide the information for choosing the appropriate sampling option. Four sampling approaches: time weighted sampling (SA1), random grab sampling (SA2), grab sampling within 6 hrs irrespective of storm size (SA3) and grab sampling within 6 hrs of medium and large storms (SA4) were analysed for annual average flow, annual average concentration and annual load. SA3 and SA4 samples are formed from the data set of SA2 using the recorded time of sampling and rainfall time. Volume weighted mass load estimation from time weighted sampling is considered as the base load because the estimation has less error (*Leecaster et al, 2002*) compared to other sampling approaches. SA2 is a random sampling that does not respond to the time of corresponding storms. SA3 does not take account of the influencing storm size but is taken within 6 hrs of the commencement of rain. SA4 is the sampling approach recommended for grab sampling by Lee et al. (*2007*) and Khan et al. (*2006*), in which grab samples were taken within 6 hrs of medium and large storm events. The volume of total runoff is calculated based on runoff coefficient, catchment area and runoff depth. The comparison of these four approaches with simulated output is presented in Fig. 6.

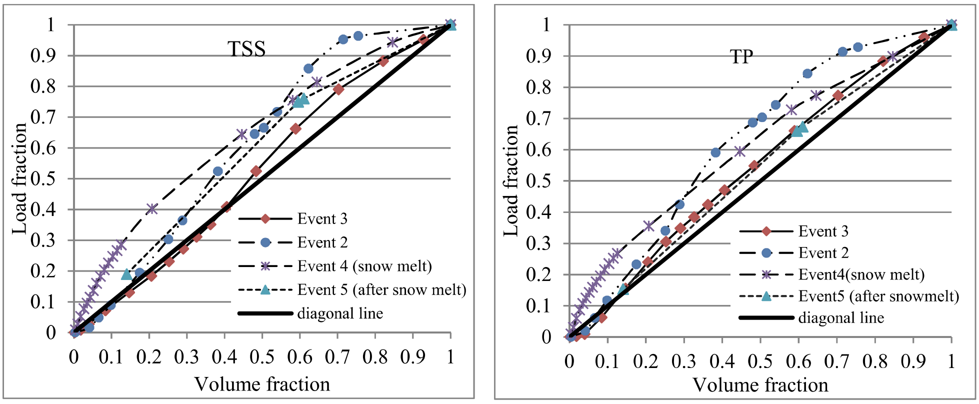

Fig. 5. First flush phenomenon for TSS and TP

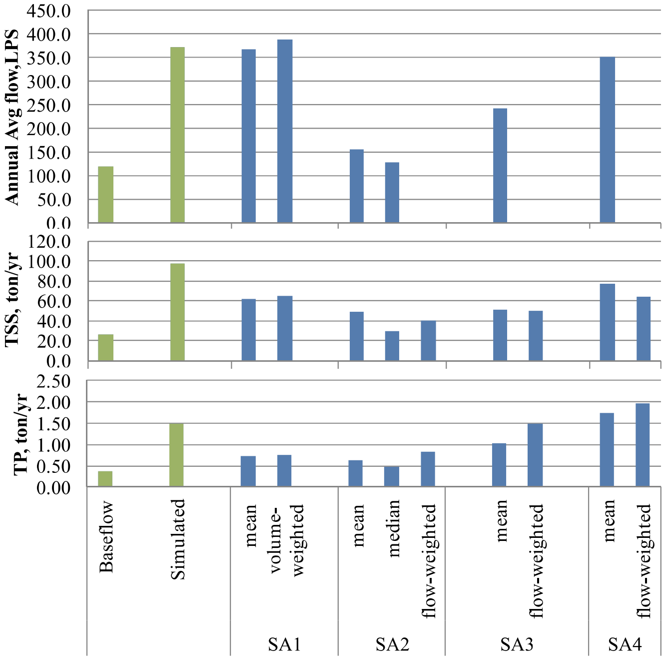

Fig. 6. Comparison of simulated annual average flow and loads with four different sampling campaigns

The SA1 sampling method with volume weighted estimation is close to the simulated flow rate and annual loads, which indicates that time weighted sampling with volume weighted calculation as specified by Leecaster et al. (*2002*) provides less error. It is considered as actual load in the analysis of sampling approaches. The uncertainty of the model in quality estimation has probably built such error and difference in TSS and TP between them. In the case of flow rates and TSSs obtained from sampling approach SA4, they are close to the estimations from SA1 and SWMM simulation at around 350 l/s and 60 tons/yr, though TPs have double the deviation. Random sampling or SA2 have often estimated low values, computing less than half flow and 2/3 loads. This is due to the fact that small rainfall or baseflows were mainly sampled in this approach. SA3, which is taken irrespective of the storm size and an usual practice, has all of its mean outputs in the middle range of SA2 and SA4. SA4 with mean estimation, on the other hand, is nearer to the actual flow, TSS and TP. This approach has limitations in identifying medium and large storms. It is difficult to predict the storm size before the rainfall ends. Alternatively, SA3 samples can be used to overcome the limitation after the storm details are retrieved. Therefore, SA3 is practical and a suitable sampling method, which assists in determining the samples of medium and large storms within 6 hrs after the start of rainfall, though it requires rainfall information and greater number of samples than SA4.

4. Conclusion and recommendation

The model is developed for the large basin in Tallinn, which was calibrated and verified for the observed storm events. Additionally, sensitivity analysis for finding sensitive parameters, imperviousness identification, first flush study to search for possibility to control initial portion of runoff and evaluation of sampling approaches are carried out and the conclusions are detailed below.

- Sensitivity analysis shows that the model is sensitive to percentage imperviousness for predicting both flow rate and peak flow. Impervious depression storage regulates the initial peak flow. Impervious surface roughness and width of catchment have weak connections to the model predictions.
- For the studied large basin, percentage imperviousness is found to be 19.7 % where the runoff coefficients for different land use varies from 0.05 to 0.57 depending on the proximity of the connection to the drainage system. The overall imperviousness is relatively low, depicting a large basin with mixed land use, which has a high impact on reducing runoff coefficient. The average depression storage for dry and wet weather is used and the effective value is found to be 0.7 mm.
- The duration of runoff is crucial when estimating event total volume. Stormflow volume has an increasing tendency with total rainfall, whereas stormflow mass load is related to intensity. In the events, pollution is attributed more to stormflow than baseflow.
- DCIA is an important factor for impervious estimation. Roads and roofs, which are directly connected to storm drainage, are crucial elements of DCIA and these impervious areas can contribute up to 75 % of runoff and 66 % to 71 % of load.
- During low intensity of rainfall, the first flush was found to be less effective. The first flush can occur later during 60 % of the runoff volume. Therefore, the implementation of treatment facilities to control initial runoff and pollution load may not be effective and more research on the first flush of large basins is required. It is found that the first flush effect during snowmelt period exists, the impact of which cannot be ignored. It will be interesting to simulate snowmelt once there are sufficient input parameters and observations.
- The reliable sampling approach at limited resource is grab sampling within 6 hrs of storm events, as these provide results close to the simulated and time weighed sampling method. This approach should focus to capture medium and large storm events.

Overall, the model development provides information about catchment's stormwater dynamics even at limited resources. The model developed in SWMM has a good performance for quantity estimation, but the quality results are in moderate accuracy. Calibration and verification using more storm events will increase the accuracy. Its applicability will increase even during the winter time once it is included with snow period simulation. Nevertheless, this study has found crucial impervious areas, impervious percentage, runoff, EMCs and pollution loads, and evaluated the sampling approaches used. The information will be helpful in planning pollution reduction strategies, implementing pollution control facilities and designing the monitoring programme in the field of stormwater management.

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5. References

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Suurlinna valgala äravoolu, veekvaliteedi ja koormuse modelleerimine

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Sisukokkuvõte. Sademevee äravoolu, saastekoormuse ja maakasutuse määratlemine on sademevee käitlemise strateegia elluviimiseks väga oluline. Modelleerimine võimaldab hinnata neid näitajaid ka piiratud andmehulga põhjal. Käesolevas uurimuses rakendati sademeveekäitlemise mudelit SWMM5 ja arendati seda Tallinna suuruse valgala tarbeks. Geograafilist informatsiooni süsteemi GIS kasutati alam-valgala ning äravoolu otseselt mõjutavate vettpidavate pinnakatetega alade piiritlemiseks ja valgala sisendi parameetrite ettevalmistamiseks. Mudelit kalibreeriti ja kontrolliti juhuslike valingvihmasadude põhjal, et hinnata saasteinete keskmisi kontsentratsioone ja aastasi koormusi. Mudel võimaldab päris hästi ennustada ärajuhtimist vajava sademevee hulka, kuid sademevee koostist ennustab ainult mõõdukal määral. Mudeli rakendamisel leiti, et kõvakattega alade suure osakaalu tõttu uuritaval valgalal jääb veepidavus alla 19,7%. Otseselt äravoolule mõju avaldavate vettpidavate pindade, eriti teede ja katuste, osakaal on suhteliselt madalam, kuid avaldab olulist mõju äravoolu kujunemisele (kuni 75%) ja koormustele (kuni 66% ja 71%). Valingvihmade ja lumesulamise aegne äravool ja koormus moodustavad olulise osa aastasest kogukoormusest. Kui rakendatakse pistelist proovivõtumetoodikat, peab see olema suunatud keskmistele ja tugevatele sajuhoogudele ja toimuma 6 tunni jooksul peale saju algust, et saada esinduslikumaid mõõtmistulemusi.

APPENDIX II CURRICULUM VITAE

1. Personal data

Name	Bharat Maharjan
Date and place of birth	25.04.1978, Lalitpur, Nepal
Address	Lalitpur-03, Nepal
Phone	+372 55686906, +977 9841404166
E-mail	bharat.maharjan@ttu.ee bmaharjan302@gmail.com

2. Education

Educational institution	Graduation year	Education (field of study/ degree)
UNESCO-IHE, Delft, The Netherlands	2011	Master degree - MSc in Municipal Water and Infrastructure
Institute of Pulchowk (IOE), Pulchowk, Lalitpur, Nepal	2009	Master degree - MSc in Environmental Engineering
Kantipur Engineering College, Dhapakhel, Lalitpur, Nepal	2003	Bachelor's Degree in Civil Engineering

3. Language competence/skills

Nepali	Native
English	Good
Hindi	Average
Newari	Mother language
Estonian	Basic

4. Professional Employment

Period	Organisation	Position
2011-2012	Multi Disciplinary Consultants (P) Ltd, Kathmandu, Nepal	Environmental Engineer
2011-2011	Himalaya College of Engineering, Kathmandu, Nepal	Lecturer
2005-2007	D.N. Construction Pvt. Ltd, Tahachal, Kathmandu, Nepal	Civil Engineer

5. Special Courses

Period	Educational Organisation	Description
25-27.06.2012	Tallinn University of Technology	Urban Water Systems: Interactions and

		integrating modelling, planning and management
2007	Nepal Engineers' Association (NEA), NGO Forum in association with UN Habitat	Training on Rain Water Harvesting System for Architects and Civil Engineers organised
Nov 2007	Institute of Engineering, Pulchowk,	Remote Sensing

6. Defended theses

Master theses: Network Generation Tool for the Reliability Analysis of Water Distribution Network. – Prof. Dr. Damir Brdjanovic (Supervisor) and Ass. Prof. Nemanja Trifunovic (Mentor).

Bachelor theses: Inclined parallel plate settler as a high rate clarifier. – Prof. Dr. Bhagwan Ratna Kansakar(Supervisor) and Ass. Prof. Ishwor Man Amatya (Supervisor).

7. Research Activity

Stormwater monitoring, water management, hydraulic and hydrologic modelling, water quality, water distribution.

8. Honours/ Awards

DoRa Scholarship, 2012
Netherland Fellowship Program, 2009

9. Scientific work

Publications and presentations:

Maharjan, B.; Pachel, K.; Loigu, E. (2016). Towards effective monitoring of urban stormwater for better design and management. Estonian Journal of Earth Sciences, 65 (3), 176−199, 10.3176/earth.2016.12.

Maharjan, B.; Pachel, K.; Loigu, E. (2016). Trends in urban stormwater quality in Tallinn and influences from stormflow and baseflow. Journal of Water Security, 2 (1), 1−11, 10.15544/jws.2016.001.

Klõga, M.; **Maharjan, B.** (2015). Temporal trends in nitrogen concentrations in Estonian rivers. Journal of Water Security, 1 (4), 37−45, 10.15544/jws.2015.004.

Maharjan, B.; Pachel, K.; Loigu, E. (2013). Urban stormwater quality and quantity in the city of Tallinn. European Scientific Journal, 3, 305−314.

Trifunović, Nemanja; **Maharjan, Bharat**; Vairavamoorthy, Kalanithy (2012). Spatial network generation tool for Water Distribution Network design and performance analysis. IWA Publishing, Water Science & Technology: Water Supply, 13 (1), 1−19, ws.2013.008.

APPENDIX III ELULOOKIRJELDUS

1. Isikuandmed

Ees- ja perekonnanimi	Bharat Maharjan
Sünniaeg ja -koht	25.04.1978, Lalitpur, Nepaal
Aadress	Lalitpur-03, Nepaal
Telefon	+372 55686906, +977 9841404166
E-mail	bharat.maharjan@ttu.ee bmaharjan302@gmail.com

2. Hariduskäik

Õppeasutus	Lõpetamise aasta	Haridus (eriala/kraad)
UNESCO-IHE, Delft, Madalmaad	2011.a.	Tehnikateaduste magister (MSc) – asulate veemajanduse ja infrastruktuuride alal
Institute of Pulchowk (IOE), Pulchowk, Lalitpur,Nepal	2009.a.	Tehnikateaduste magister (MSc) keskkonnatehnika alal
Kantipur Engineering College, Dhapakhel, Lalitpur, Nepal	2003.a.	Bakalaureusekraad ehituse alal

3. Keelteoskus

Keel	Tase
Nepaali keel	rahvuskeel
Inglise keel	hea
Hindi keel	kesktase
Newari keel	emakeel
Eesti keel	algtase

4. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2011-2012.a	Multi Disciplinary Consultants (P) Ltd, Kathmandu, Nepaal	Keskkonnakaitse insener
2011-2011.a	Himaalaja ehituskolledzh, Kathmandu, Nepaal	Lektor
2005-2007.a.	D.N. Construction Pvt. Ltd, Tahachal, Kathmandu, Nepaal	Ehitusinsener

5. Täiendusõpe

Periood	Täiendusõppe korraldaja	Kirjeldus
25.-27. juuni	Tallinna tehnikaülikool	Linnade veesüsteemid:

2012.a.		modelleerimise, planeerimise ja veemajanduse vastastikused toimed ja lõimumine
2007.a.	Nepaali inseneride ühing, mittetulundusühenduste foorum ja ÜRO Asulate ja linnade säästva arengu programm *(UN Habitat)*	Sademevee kogumise koolitus arhitektidele ja ehitusinseneridele
November 2007.a.	Pulchowk'i inseneriteaduste instituut	Kaugseire

6. Kaitstud lõputööd

Magistritöö: Network Generation Tool for the Reliability Analysis of Water Distribution Network. – Prof .Dr. Damir Brdjanovic (Supervisor) and Ass. Prof. Nemanja Trifunovic (Mentor).

Bakalaureusetöö: Inclined parallel plate settler as a high rate clarifier. – Prof .Dr. Bhagwan Ratna Kansakar (Supervisor) and Ass. Prof. Ishwor Man Amatya (Supervisor).

7. Uurimistöö

Sademevee seire, veemajandus, hüdrauliline ja hüdroloogiline modelleerimine, vee kvaliteet, veevarustus.

8. Teadusauhinnad

DoRa stipendium, 2012
Netherland Fellowship Program, 2009

9. Teadustöö

Avaldatud tööd ja ettekanded:

Maharjan, B.; Pachel, K.; Loigu, E. (2016). Towards effective monitoring of urban storm water for better design and management. Estonian Journal of Earth Sciences, 65 (3), 176−199, 10.3176/earth.2016.12.

Maharjan, B.; Pachel, K.; Loigu, E. (2016). Trends in urban storm water quality in Tallinn and influences from stormflow and baseflow. Journal of Water Security, 2 (1), 1−11, 10.15544/jws.2016.001.

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Trifunović, Nemanja; **Maharjan, Bharat**; Vairavamoorthy, Kalanithy (2012). Spatial network generation tool for Water Distribution Network design and performance analysis. IWA Publishing, Water Science & Technology: Water Supply, 13 (1), 1−19, ws.2013.008.

DISSERTATIONS DEFENDED AT TALLINN UNIVERSITY OF TECHNOLOGY ON *CIVIL ENGINEERING*

1. **Heino Mölder**. Cycle of Investigations to Improve the Efficiency and Reliability of Activated Sludge Process in Sewage Treatment Plants. 1992.

2. **Stellian Grabko**. Structure and Properties of Oil-Shale Portland Cement Concrete. 1993.

3. **Kent Arvidsson**. Analysis of Interacting Systems of Shear Walls, Coupled Shear Walls and Frames in Multi-Storey Buildings. 1996.

4. **Andrus Aavik**. Methodical Basis for the Evaluation of Pavement Structural Strength in Estonian Pavement Management System (EPMS). 2003.

5. **Priit Vilba**. Unstiffened Welded Thin-Walled Metal Girder under Uniform Loading. 2003.

6. **Irene Lill.** Evaluation of Labour Management Strategies in Construction. 2004.

7. **Juhan Idnurm**. Discrete Analysis of Cable-Supported Bridges. 2004.

8. **Arvo Iital**. Monitoring of Surface Water Quality in Small Agricultural Watersheds. Methodology and Optimization of monitoring Network. 2005.

9. **Liis Sipelgas**. Application of Satellite Data for Monitoring the Marine Environment. 2006.

10. **Ott Koppel**. Infrastruktuuri arvestus vertikaalselt integreeritud raudtee-ettevõtja korral: hinnakujunduse aspekt (Eesti peamise raudtee-ettevõtja näitel). 2006.

11. **Targo Kalamees**. Hygrothermal Criteria for Design and Simulation of Buildings. 2006.

12. **Raido Puust**. Probabilistic Leak Detection in Pipe Networks Using the SCEM-UA Algorithm. 2007.

13. **Sergei Zub**. Combined Treatment of Sulfate-Rich Molasses Wastewater from Yeast Industry. Technology Optimization. 2007.

14. **Alvina Reihan**. Analysis of Long-Term River Runoff Trends and Climate Change Impact on Water Resources in Estonia. 2008.

15. **Ain Valdmann**. On the Coastal Zone Management of the City of Tallinn under Natural and Anthropogenic Pressure. 2008.

16. **Ira Didenkulova**. Long Wave Dynamics in the Coastal Zone. 2008.

17. **Alvar Toode**. DHW Consumption, Consumption Profiles and Their Influence on Dimensioning of a District Heating Network. 2008.

18. **Annely Kuu**. Biological Diversity of Agricultural Soils in Estonia. 2008.

19. **Andres Tolli**. Hiina konteinerveod läbi Eesti Venemaale ja Hiinasse tagasisaadetavate tühjade konteinerite arvu vähendamise võimalused. 2008.

20. **Heiki Onton**. Investigation of the Causes of Deterioration of Old Reinforced Concrete Constructions and Possibilities of Their Restoration. 2008.

21. **Harri Moora**. Life Cycle Assessment as a Decision Support Tool for System optimisation – the Case of Waste Management in Estonia. 2009.

22. **Andres Kask**. Lithohydrodynamic Processes in the Tallinn Bay Area. 2009.

23. **Loreta Kelpšaitė**. Changing Properties of Wind Waves and Vessel Wakes on the Eastern Coast of the Baltic Sea. 2009.

24. **Dmitry Kurennoy.** Analysis of the Properties of Fast Ferry Wakes in the Context of Coastal Management. 2009.

25. **Egon Kivi**. Structural Behavior of Cable-Stayed Suspension Bridge Structure. 2009.

26. **Madis Ratassepp**. Wave Scattering at Discontinuities in Plates and Pipes. 2010.

27. **Tiia Pedusaar**. Management of Lake Ülemiste, a Drinking Water Reservoir. 2010.

28. **Karin Pachel**. Water Resources, Sustainable Use and Integrated Management in Estonia. 2010.

29. **Andrus Räämet**. Spatio-Temporal Variability of the Baltic Sea Wave Fields. 2010.

30. **Alar Just**. Structural Fire Design of Timber Frame Assemblies Insulated by Glass Wool and Covered by Gypsum Plasterboards. 2010.

31. **Toomas Liiv**. Experimental Analysis of Boundary Layer Dynamics in Plunging Breaking Wave. 2011.

32. **Martti Kiisa**. Discrete Analysis of Single-Pylon Suspension Bridges. 2011.

33. **Ivar Annus**. Development of Accelerating Pipe Flow Starting from Rest. 2011.

34. **Emlyn D. Q. Witt**. Risk Transfer and Construction Project Delivery Efficiency – Implications for Public Private Partnerships. 2012.

35. **Oxana Kurkina**. Nonlinear Dynamics of Internal Gravity Waves in Shallow Seas. 2012.

36. **Allan Hani**. Investigation of Energy Efficiency in Buildings and HVAC Systems. 2012.

37. **Tiina Hain**. Characteristics of Portland Cements for Sulfate and Weather Resistant Concrete. 2012.

38. **Dmitri Loginov**. Autonomous Design Systems (ADS) in HVAC Field. Synergetics-Based Approach. 2012.

39. **Kati Kõrbe Kaare**. Performance Measurement for the Road Network: Conceptual Approach and Technologies for Estonia. 2013.

40. **Viktoria Voronova**. Assessment of Environmental Impacts of Landfilling and Alternatives for Management of Municipal Solid Waste. 2013.

41. **Joonas Vaabel**. Hydraulic Power Capacity of Water Supply Systems. 2013.

42. **Inga Zaitseva-Pärnaste**. Wave Climate and its Decadal Changes in the Baltic Sea Derived from Visual Observations. 2013.

43. **Bert Viikmäe**. Optimising Fairways in the Gulf of Finland Using Patterns of Surface Currents. 2014.

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