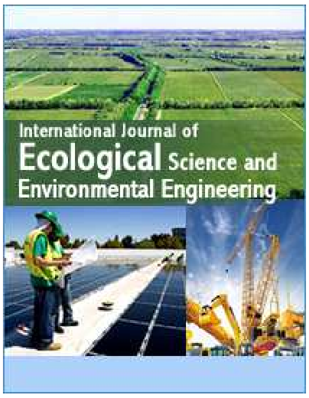
International Journal of Ecological Science and Environmental Engineering
2014; 1(3): 80-90
Published online December 20, 2014 (http://www.aascit.org/journal/ijesee)
ISSN: 2375-3854



Keywords
Hydrology & Water Resoruce,
Pollution,
Sewers & Drains,
Sewage Treatment & Disposal

Received: November 18, 2014
Revised: December 08, 2014
Accepted: December 09, 2014

Modelling of stormwater discharge and quality in urban area

Tiit Koppel, Anatoli Vassiljev, Raido Puust, Janek Laanearu

Department of Mechanics, Tallinn University of Technology, Tallinn, Estonia

Email address
janek.laanearu@ttu.ee (J. Laanearu)

Citation
Tiit Koppel, Anatoli Vassiljev, Raido Puust, Janek Laanearu. Modelling of Stormwater Discharge and Quality in Urban Area. *International Journal of Ecological Science and Environmental Engineering.* Vol. 1, No. 3, 2014, pp. 80-90

Abstract
This paper presents the stormwater measurements and modelling results of contaminated rainwater discharge in the capital of Estonia, Tallinn. Pollutant concentration and runoff was measured in six urban area subcatchments (0.56 – 481 ha in size). Rainfall events were monitored during one year (2008). Selected subcatchments cover areas of transportation, residential and commercial areas. The water flow and quality were modelled by the USEPA SWMM 5 model. The accuracy of water quality modelling depends on the precision of stormwater hydraulic modelling and precipitation measurements. Water quality was modelled for concentrations of suspended solids. It was found that concentration of suspended solids may have high peak values at the start of water flow. Differences between flow weighted and non-flow weighted average concentrations are analysed here for different sampling intervals.

1. Introduction

Urban runoff pollution has been studied during several decades. First attempts to identify specific sources of runoff pollution were made by American Public Works Association (APWA, 1969). The report pointed out that the dust and dirt fraction is the most significant component. The physical and chemical characteristics of the dust and dirt fraction were further investigated by Sartor and Boyd (1972). It was concluded that the major component of street dirt was consistently found to be similar to common sand silt (mineral-like matter). Pitt and Amy (1973) concentrated on toxic material analysis of street surface contaminants. It was found that in terms of water pollution, the most important metallic elements in street dirt are: Chromium (Cr), Copper (Cu), Lead (Pb), Nickel (Ni), Strontium (Sr), Titanium (Ti), Zinc (Zn), and Zirconium (Zr).

Models applicable to stormwater quality and quantity appeared in the early 1970s (Zoppou, 2001; Bach *et al.* 2014). The basic components of an urban stormwater model are: (1) rainfall-runoff modelling and (2) wash-off modelling. In water quality modelling, part (1) is responsible for build-up of pollutants and part (2) routing of those pollutants through water infrastructure. It is clear that as pollutant concentrations and loads cannot be estimated without having estimated the flows, most water quality models include hydrologic or hydraulic components to simulate the movement of water through the urban catchment. Low impact urban stormwater drainage models have been reviewed by Elliott and Trowsdale (2007). One of the most widely used software packages for watershed modelling is the U.S. Environmental Protection Agency's (USEPA's) Stormwater Management Model (SWMM) that dates back to several decades (ME 1971). SWMM development and its water quality formulations are described in Huber and Dickinson (1992), Sutherland (2003) and Rossman (2009).

In addition to simple water quantity and quality analysis, stormwater modelling may include various other aspects, including optimisation (Lee *et al.* 2012) and uncertainty analysis (Dotto *et al*. 2012, 2014). A stormwater quality model should be calibrated and verified against available data before its use. The efficiency of the model can be evaluated by the method used in Vassiljev (2006). In general, the model performance can be improved by using a large size of calibration datasets and by selecting calibration data that are representative of all data (Sun and Bertrand-Krajewski, 2012).

Although stormwater is often viewed by the public as being as clean as rain, in fact it contains significant quantities of constituents more commonly associated with municipal and/or industrial wastewater (Durrans, 2003). Stormwater runoff is regarded as the leading source of water pollution in the United States (Lee *et al*. 2007). It is complicated to determine pollution fluxes when the stormwater subcatchment is located on the coastal area (Laanearu *et al.* 2011). Strategies for handling stormwater are needed at different decision levels, including political, regional and local scale. All of the institutions need information and a clear understanding of the possibilities that are at risk as well as the main consequences of each decision (Barbosa *et al*. 2012). Priority pollutants in urban stormwater have been investigated from different perspectives: (a) separate storm sewers (Zgheib *et al*. 2012) and (b) combined sewers (Gasperi *et al*. 2011). The priority pollutants that are essential for quality analysis are also listed in Eriksson *et al*. (2007). It can be concluded from various case studies that volatile organic compounds are mainly wastewater side and concentrations of pesticides and Zn are similar in both separate and combined systems.

The aims of study are to investigate water quality indicators from different type of subcatchments in Tallinn (Estonia) and to compare the measured values with allowable maximum concentration limits. Special attention was paid to estimating the optimal time interval of pollutant concentration measurements for water quality analysis and examining the average indicators of pollution. Measurements were carried out at outlets of subcatchments and therefore the modelling of stormwater system was necessary in order to gather valuable information at other subparts of subcatchment. Based on analysis the runoff coefficients for different types of catchments were determined, considering also seasonal effects. The results of current study were presented as the base information for drafting the methodology of flow and sampling measurements for stormwater management tools for local authorities (Koppel *et al.* 2008).

2. Measurements and Modelling

2.1. Study Site

Current study is carried out in Tallinn that is the largest city in Estonia, serving about 1/3 of its population. Tallinn is located in the north-eastern part of Europe. The monthly average values for air temperature and precipitation in 2008 are presented in Table 1. A special monitoring programme was completed in 2008 (carried out by Sweco Projekt AS, Estonian Environmental Research Centre and Tallinn University of Technology). Water flow and water quality within different subcatchment types were investigated and compared. The results have been used in various further studies, including Tallinn City Stormwater Strategy for 2030 (Tallinn 2012) and in the modelling of stormwater flow routes (Laanearu *et al.* 2009). Six subcatchments were selected for the measurements (Fig. 1). Table 2 lists general characteristics of the subcatchments. Five subcatchments shown in Fig. 1 have been selected to cover typical city areas (transportation, two types of small residential areas, commercial area). In the present paper the dynamics of stormwater flow and pollution in different seasons is investigated and compared with modelled results.

Table 1. *Monthly average air temperature and precipitation values for 2008.*

Month	Average precipitation (mm)	Average temperature (°C)
January	57	-0.9
February	63	1
March	63	0.4
April	39	6.6
May	0.5	10.3
June	43 - 177*	14.4
July	63	16.5
August	123 - 243*	15.7
September	49	10.2
October	104	8.6
November	52 - 128*	2.8
December	55	-1.2

*Minimum and maximum values are presented, instead of country's average (based on data available at EMHI 2013)

Table 2. *Subcatchments.*

Number	Subcatchment name	Area (ha)	Type of the area	Number of modelled manholes
1	Rocca-al-Mare	12.06	commercial	222
2	Õismäe PS	481	mixed land use	Not modelled
3	Õismäe Street	0.72	residential	12
4	Sütiste Street – Sõpruse Street	9.15	transportation	48
5	Võru Street	0.56	residential	20
6	Vabaduse Street	4.13	transportation	24

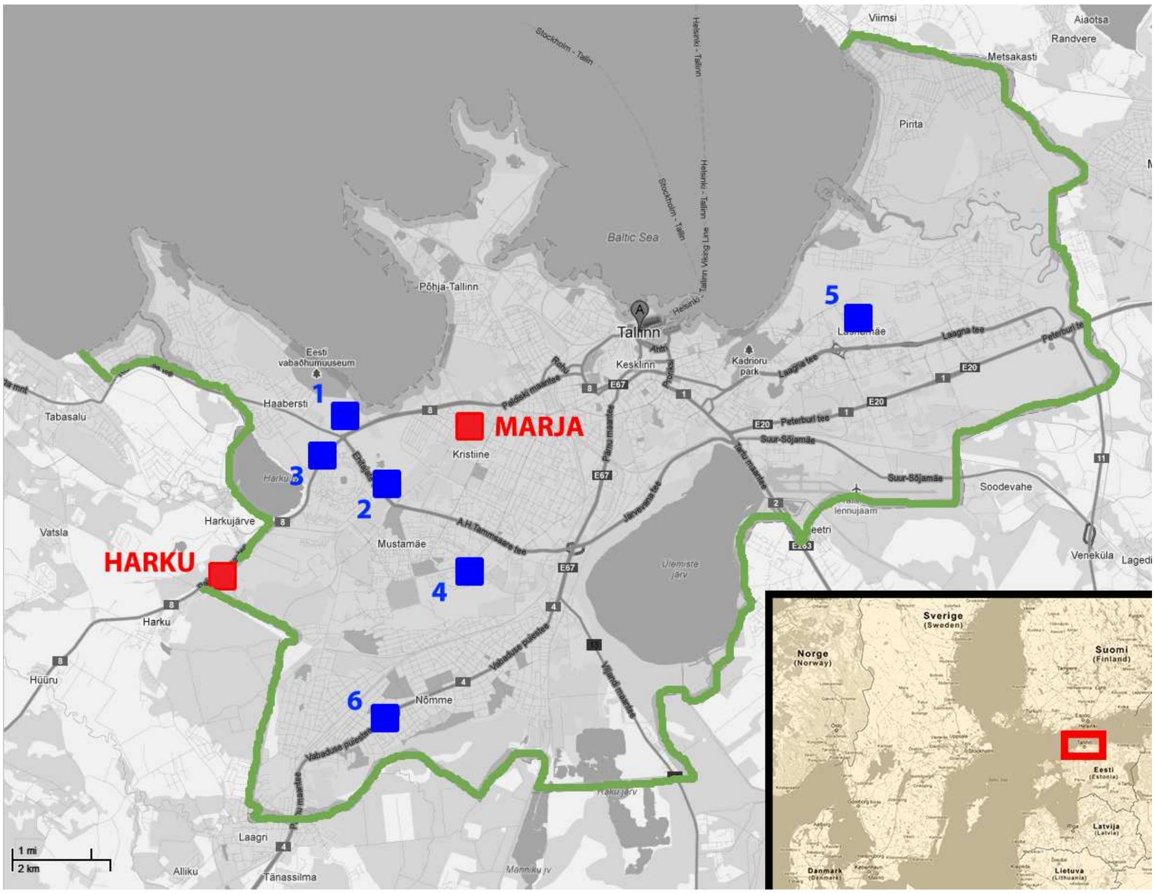


Fig. 1. Map of Tallinn city with points of measurements (1-6) and meteorological measurement stations Harku and Marja.

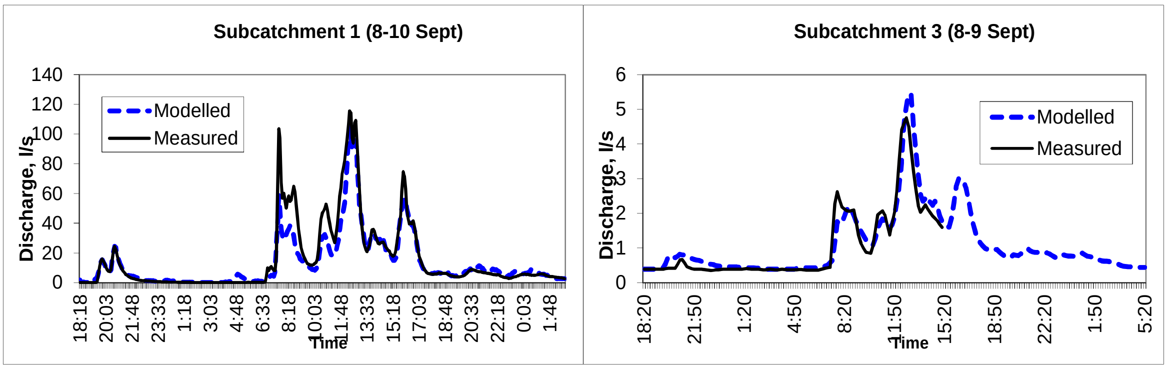


Fig. 2. Modelled and measured flows at subcatchments 1 and 3.

2.2. Measurements (Rainfall, Flow, Quality)

For accurate urban rainfall-runoff prediction, the assessment of rainfall should be carried out (Fletcher et al. 2014). Measurements for current study were performed during the rainfall events: 11-14 March, 10-13 June, 19-22 August and 8-10 September in 2008. Rainfall intensity with time intervals 5-10 minutes (cumulative rainfall during 5 or 10 minutes) was measured in the Harku meteorological station and in one portable station installed in Marja Street in Tallinn, as indicated in Fig. 1. Rainfall varies considerably in space and time, and reveals the random process character in many aspects (Laanearu *et al*. 2009). During the field study experiment in Tallinn, the precipitation data were collected close to the stormwater networks under investigation. The meteorological measurements during the rainy season of the Tallinn area include the rainfall records from: 1) 8-14 March; 2) 10-12 June; 3) 20-25 August; and 4) 8-10 September 2008. Main storms corresponding to representative rainfall events during 2008 are summarised in Table 3. Depending on the rainfall characteristics (intensity, duration, dry period, etc.), many runoff situations are possible, and different amounts of gathered pollution from a subcatchment can be washed off. Therefore, the term of representative rainfall was introduced in USEPA 1992. The representative rainfall includes two criteria: 1) the intensity of the rain must be greater than 2.54 mm per 24 hours, and 2) the dry period prior to the rainfall event must be longer than 24 hours (DE 2002, Andresmaa *et* *al*. 2005). Where feasible, the depth of a storm and its duration should not vary by more than 50% as compared to the depth and duration of the local average storm event (USEPA 1992). Year 2008 storms analysed in Laanearu *et al*. (2009) showed that previously mentioned rain events can be classified as the representative rainfalls.

Table 3. *Measured storms and characteristics.*

Rain starts		Rain ends		Accumulation depth	24 hour intensity	Prior dry period
Date	*Time*	*Date*	*Time*			
12/03	08:57	14/03	09:17	10.08 mm	5.005	85h
20/08	09:34	20/08	19:34	4.19 mm	10.056	45h
24/08	01:04	25/08	10:24	8.94 mm	6.436	44h
09/09	05:36	10/09	04:06	11.81 mm	12.597	24h

In addition to collecting samples of stormwater, the data characterising the flow rate and flow volume for each stormwater discharge were measured using automatic flow measurement devices (Marsh-McBirney Flo-Dar area/velocity radar flow meter sensor and Flo-Tote 3 sensor electromagnetic area/velocity flow meter sensor). Flow rate data are necessary to collect flow-weighted composite samples and to combine proportional volumes of individually collected samples. Water discharge was measured by an automatic measurement system from the beginning of discharge with a time interval of 1 hour in March and 5-10 minutes in other months.

This study focuses onto water quality that is an important indicator used in the management of stormwater systems. Several countries have published guidance for the estimation of stormwater quality. Such instructions have been prepared in Estonia as well (Andresmaa *et al*. 2005). Estonian guidelines have been prepared on the basis of the EPA Water Sampling Guidance from the USA (DE 2002). Two types of samples may be collected according to this guide – flow-weighted composite and individual samples. Flow-weighted composite samples were collected by an automatic sampling system (Manning Portable Peristaltic 24 Bottles Sampler and WaterSam WS Porti 12 Bottles Water Sampler) during the first two hours with intervals of 5 or 10 minutes from all sites to determine all water quality characteristics except suspended solids. Start time for the composite samples was not later than 30 minutes after the beginning of the discharge. Series of individual samples were collected to reflect the dynamics of total suspended solids (for mineral and organic constituents). Pollutants concentrations in water samples and in rainwater are presented in Table 4. Quality of sampling and analyses was guaranteed by the staff of an accredited laboratory and by modern instruments for water flow measurements and composite samples collection.

Table 4. *Constituent concentrations in water samples.*

Substance (unit)	Subcatchment number (Min | Max)						
	Marja	5	6	1	4	2	3
1,2-dichloroethane (µg/l)	<0.01 <0.1	<0.1 <1	<0.1 <1	<0.1 <1	<0.1 <1	<0.1 <1	<0.1 <1
Monobasic phenolic (µg/l)	2.6 17.2	9.5 13.8	<2 8.7	<2 12.4	4.2 24.7	6.3 10.1	<2 16.5
Dibasic phenol (µg/l)	<10	<10	<10	<10	<10	<10	<10
Ag (mg/l)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
a-Hexachlorocyclohexane (ng/l)	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10
Aldrin (ng/l)	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10
AOX (µg/l)	n/a	32	n/a	n/a	n/a	114	64
As (mg/l)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
BOD7 (mgO2/l)	3.3 7	<3 9.5	10 34	6.2 70	6.4 55	5.4 120	3.5 37
Cd (mg/l)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
CN- (µg/l)	<3 6.1	<3 3.4	<3 49	<3 7.5	<3 4.3	<3 9	<3 3.3
Cr (mg/l)	<0.02	<0.02	<0.02 0.025	<0.02	<0.02	<0.02	<0.02
Cu (ng/l)	<0.02 0.038	<0.02 0.048	0.02 0.308	<0.02 0.093	<0.02 0.062	<0.020.118	<0.02 0.062
Dieldrin (ng/l)	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10
Endrin (mg/l)	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10
F- (mg/l)	<0.1	<0.1 0.16	<0.1 0.19	<0.1 0.15	<0.1	<0.1 0.32	<0.1 0.15
g-Hexachlorocyclohexane (ng/l)	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10
Hexachlorobenzene (µg/l)	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10
Hexachlorobutadiene (µg/l)	<0.1	<0.1 0.28	<0.1	<0.1	<0.1	<0.1	<0.1
Hg (µg/l)	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

Substance (unit)	**Subcatchment number (Min | Max)**						
	Marja	**5**	**6**	**1**	**4**	**2**	**3**
			0.15		0.18		0.08
Suspended solids (mg/l)	<2 36	<2 340	28 3850	6 1214	24 616	<2 4366	<2 210
Suspended solids, mineral (mg/l)	n/a	<2 114	12 236	2 99	1 161	<2 304	<2 45
Suspended solids, organic (mg/l)	n/a	<2 92	15 134	3 35	10 112	<2 188	<2 34
Suspended solids, VSS (mg/l)	n/a	3 30	32 176	30 494	80 196	21 690	3 49
Isodrin (mg/l)	n/a	<10	n/a	n/a	n/a	<10	n/a
Chloroform (µg/l)	0.1 0.36	<0.5	0.23 1.57	<0.6	0.88	0.57 0.81	0.2 0.52
Oil (µg/l)	<20 120	50 275	<20 4340	60 880	20 750	400 1550	<20 80
Ni (mg/l)	<0.02	<0.02	<0.02	<0.02 0.028	<0.02	<0.02	<0.02
Nitrogen; total, Kj. (mg/l)	2.8 5.6	3.9 8.9	3.6 9.7	3.3 15	3.2 6	3.2 10	3 6.6
p,p´-DDD (ng/l)	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10
p,p´-DDE (ng/l)	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10
p,p´-DDT (ng/l)	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10	<5 <10
PAH, sum µg/l	0.12 0.45	0.1 0.22	<0.1 6.3	<0.1 0.2	0.1 1.3	0.3 1.85	<0.1 0.4
Pb (mg/l)	<0.04	<0.04	<0.04 0.079	<0.04	<0.04	<0.04	<0.04
PCB, sum (ng/l)	<30	<30	<30	<30	<30	<30	<30
pH	7.28 7.89	7.19 8.44	5.56 7.97	6.57 7.66	6.95 7.86	6.93 7.69	6.92 7.97
Phosphorus, total (mg/l)	<0.02 0.25	0.11 0.46	0.23 2.3	0.17 0.31	0.32 1.6	0.51 18	0.24 0.46
Sb (mg/l)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Sn (mg/l)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Zn (mg/l)	0.02 0.046	<0.02 0.066	0.057 1.11	0.075 0.169	0.07 0.173	<0.020.2	0.036 0.347
Tetrachloroethene (µg/l)	<0.1 0.19	<0.1 1.65	<0.1 0.52	<0.1 0.31	<0.1 0.34	<0.1 0.6	<0.1 0.18
Carbon tetrachloride (µg/l)	<0.1 0.17	<0.1 0.16	<0.1 0.62	<0.1 0.28	<0.1 0.28	<0.1 0.28	<0.1 0.21
Trichloroethene (µg/l)	<0.1	<0.1 0.32	<0.1 0.5	<0.1 0.16	<0.1 0.12	<0.1 0.26	<0.1
Trichloromethane (µg/l)	0.16 0.34	0.15 0.38	0.12 0.34	0.1 0.41	<0.1 0.39	<0.1 0.28	<0.1 0.14

2.3. Modelling and Calibration

Stormwater modelling tools are used for site planning and future predictions. In the current study the USEPA's Storm Water Management Model (SWMM) software was used for modelling (Rossman 2009). The software is widely used throughout the world for planning, analysis and design related to stormwater runoff, combined sewers, sanitary sewers, and other drainage systems in urban areas, with many applications in non-urban areas as well. This is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. The runoff component of SWMM operates on a collection of subcatchment areas that receive precipitation and generate runoff and pollutant loads. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM tracks the quantity and quality of runoff generated within each subcatchment. The flow rate, flow depth, and quality of water in each pipe and channel during a simulation period are comprised of multiple time steps. Topology data was obtained from AS Tallinna Vesi (Tallinn Water Company) database. Raw data were processed and analysed. Information on the elevation of pipes and wells was checked with special care. Dynamic wave routing was used for water flow modelling. This method enables solving the complete one-dimensional Saint-Venant equations, resulting in most accurate results in terms of theory. Two indicators of quality of calibration were used Nash-Sutcliffe efficiency (NSE) and percent bias, PBIAS (Moriasi, 2007). The NSE was calculated by formula Eq. (1) (Nash and Sutcliffe, 1970).

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right)^2}{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{mean} \right)^2} \right] \quad (1)$$

where Y_i^{obs} is the ith observation for the constituent being evaluated, Y_i^{sim} is the ith simulated value for the constituent being evaluated, Y^{mean} is the mean of observed data for the constituent being evaluated, and n is the total number of observations. NSE ranges between $-\infty$ and 1.0, with NSE = 1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance. Percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than observed (Gupta et al., 1999). The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. PBIAS is calculated with Eq. (2).

$$PBIAS = \frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right) \times 100}{\sum_{i=1}^{n} Y_i^{obs}} \quad (2)$$

3. Results & Discussion

3.1. Water Flow & Quality

The collected data were used for modelling both the water flow and the quality. Suspended solids were used only for water quality modelling because other constituents were measured using a flow-weighted composite approach and without flow dynamics. Calibration of a stormwater system is a difficult task due to the variation of rain and land use categories around the catchment (Martin, 1983). Observed water flow and rainfall data from March were used for the model calibration and data observed in other months were used for simulations. Our subcatchments are mainly covered with impervious areas. Therefore calibration parameters for flow modelling were Depression Storage and Manning's n for overland flow over the impervious portion of the subcatchment. Table 5 presents the calibration results. When modelling water quality the exponential function was used for both buildup and wash-off processes. Buildup rate constant (1/days) was used for calibration of buildup process. Wash-off exponent was used as parameter when calibrating wash-off process. Results of calibration are presented in Table 6 (only subcatchments 1 and 6 were modelled). From Table 5 and Table 6, it can be concluded that modelled water flow corresponded well with measured flow and less satisfying results were accomplished for water quality modelling. It may be because of water flow processes are treated more sophistically in SWMM model than processes describing water quality. Water quality dynamics is represented by a simple exponential function in SWMM. Calibration also showed that results of modelling depend on delineation of subcatchments. Delineation may be very detailed (each manhole forms its own subcatchment) or less detailed when subcatchment includes several manholes. Fig. 2 shows the results of the water flow simulation on some subcatchments in different months. Results in Fig. 2 show that the correlation of measured and modelled flows is acceptable. Nearly all of the rainfall over the commercial subcatchment becomes runoff (Fig. 2a). The residential subcatchment (Fig. 2b) is partly covered by a pervious area, thus not all rainfall becomes runoff. Apparently the reason for the less satisfying correlation between the modelled and measured flow rates in the stormwater system is related to the precipitation measurement station, which was located rather apart from the stormwater network under investigation (see Fig. 1). The runoff coefficients for the commercial area were: March – 0.61; June – 0.41; August – 0.62; September – 1.00 and for the residential area: March – 0.41; June – 0.19; August – 0.54; September – 0.77. In addition to the spatially varying rainfall, rainwater depression storage in the impervious catchment area may also play a role.

Table 5. *Results of calibration of water flow models.*

Number (See table 2)	Depression Storage (mm)	Manning's n	NSE	PBIAS
1	0.15	0.013	0.71	4.01
3	0.29	0.014	0.92	-8.10
4	0.15	0.012	0.55	20.62
5	0.15	0.013	0.50	-23.98
6	0.17	0.014	0.42	23.52

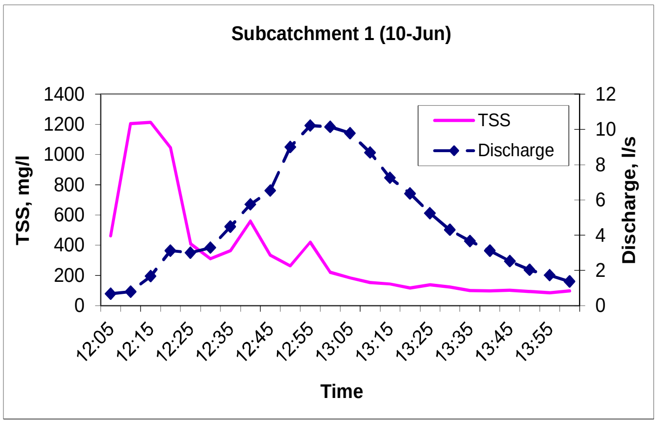
Table 6. *Results of calibration of water quality (March).*

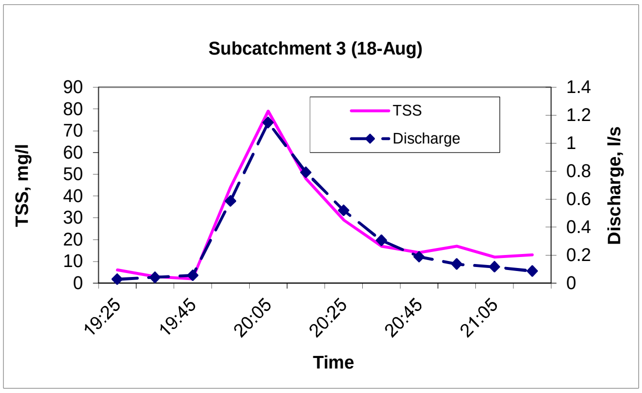
Number (See table 2)	Buildup rate constant (1/days)	Washoff exponent	NSE	PBIAS
1	0.2	1.0	0.52	30.1
6	0.2	1.0	0.55	-14.1

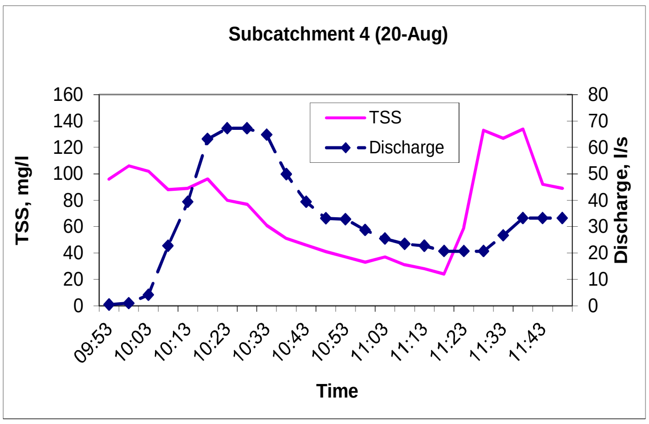
A number of water quality indicators have been estimated from samples in six measurement stations. Chemical analyses were carried out by the Central Lab of Estonian Environmental Research Centre. Table A1 (Appendix A) lists water quality indicators with their method of concentration estimations and available upper limits. Dynamics of water quality was modelled for concentrations of suspended solids. Modelled concentrations of suspended solids are in good agreement with the measured values. Average values of suspended solids are presented in Table 7. Dynamics of the concentration and water discharge are compared in Fig. 3 plots for subcatchments 1, 3, 4 and 6. Fig. 3 shows that sometimes maximal concentrations were observed at the beginning of water discharge (Fig. 3a) but at other times they occurred at the second flow wave (Fig. 3c). For a residential area (Fig. 3b), correlation between the concentrations and the water flow rate is very good. Usually concentrations increase much faster than water discharge and therefore maximum concentrations are observed earlier than maximal water discharge. Modelling indicated that the accuracy of the water quality modelling depends essentially on the accuracy of the water flow modelling. Fig. 4 shows that even good accuracy of the water flow modelling does not guarantee good accuracy of the water quality modelling. The reason is that the water quality depends on many other factors besides the water flow.

Table 7. *Total suspended solids based on the period and subcatchment.*

Subcatchment	Average concentration of suspended solids (mg/l)			
	March	*June*	*August*	*September*
1	108	312	60	8
3	44	52	52	34
4	184	516	68	126
5	90	78	90	14
6	2140	132	90	148







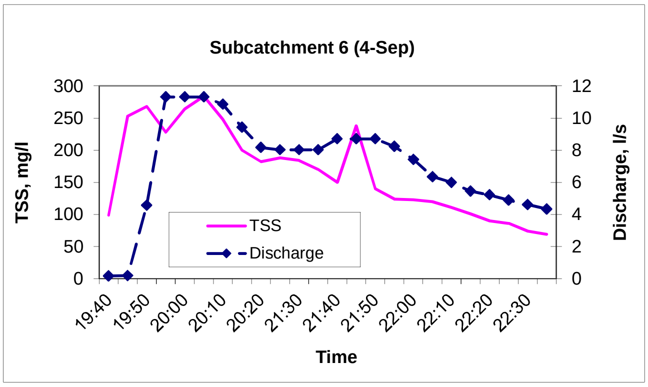
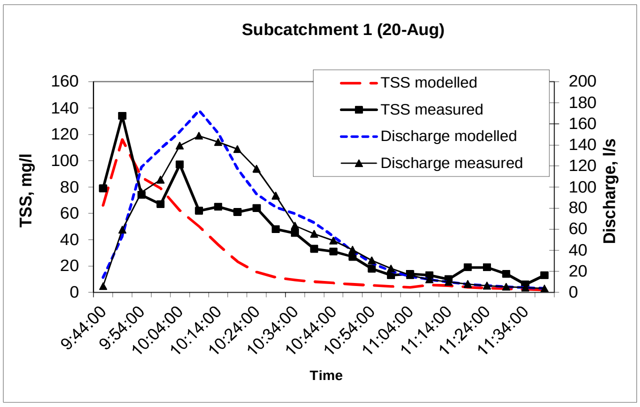


Fig. 3. *Concentrations and flow discharges for different subcatchment types: (a) commercial; (b) residential; and (c)-(d) transportation.*



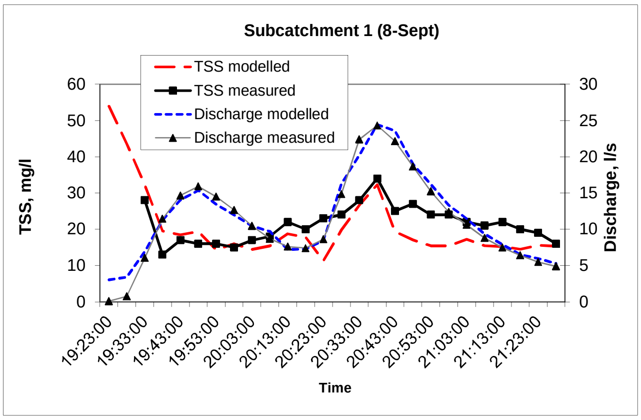


Fig. 4. *Modelled and measured water flows and suspended solids in August and in September (subcatchment 1).*

3.2. Analyses of Sampling Interval

In some circumstances only time-based water sampling is planned. The number of sampling bottles is limited, and therefore it is important to determine the maximal possible time interval for accurate water quality measurements to a full rainfall event with a minimal cost. Data of suspended solids collected in this project allow us to compare two types of average concentrations: (a) arithmetic average concentration; (b) flow-weighted average concentration. Flow-weighted average concentration was considered accurate here and it was compared against arithmetic average concentration with various sampling intervals. Arithmetic average concentration was calculated using a formula:

$$\overline{C_a} = \frac{\sum_i c_i}{n} \quad (3)$$

where

$\overline{C_a}$ - average concentration;

c_i - concentration in time i;

n - number of measurements.

Flow-weighted average concentration was estimated by the formula:

$$C_v = \frac{\sum_{i=1}^{n-1} (\frac{c_i + c_{i+1}}{2}) * W_{i-(i+1)}}{W} \quad (4)$$

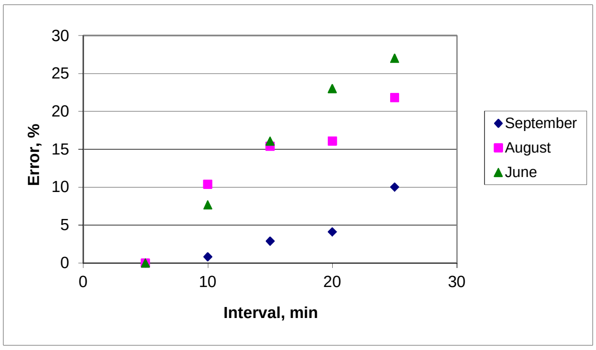
where

c_i, c_{i+1} - concentrations in time i, $i+1$;

$W_{i-(i+1)}$ – water flow between in times i, $i+1$;

W – total water flow during measurements.

Results of calculations are presented in Fig. 5 (a, b). It can be concluded for both subcatchments that an overall error for time intervals of 5 and 10 min is at an acceptable level (errors around 10%). If measurement intervals are increased, the overall error increases also (depending on time and interval up to 25% for a 25 min interval).



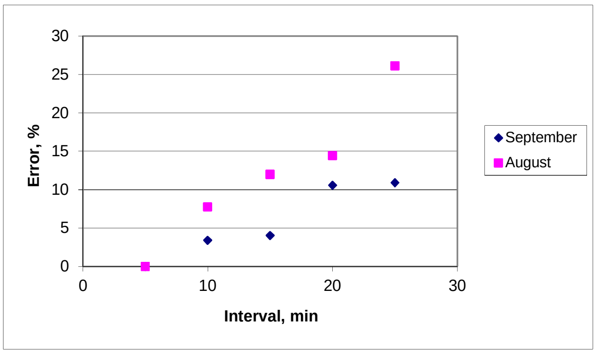


Fig. 5. Differences (errors) between flow weighted and non-flow weighted average concentrations for different sampling intervals (subcatchments 1 and 4).

4. Conclusions

Results of the measurements listed in Table 4 show that most pollutants concentrations do not exceed the upper limits presented in Table A1 (Appendix A). Only concentrations of BOD7, Nitrogen (N) and Phosphorus (P) indicators were higher than upper limit values (RT 2001). Concentrations of BOD7 and P were highest in subcatchment 2 (combined sewers). Maximum concentration was measured in June 2008. Concentration of N was comparatively high in all subcatchments under investigation, and revealed the highest value in the commercial area (subcatchment 1) that was measured in June. In subcatchment area 6 (transportation area), concentration of oil measured in March was very close to its limiting value.

It was shown that the accuracy of water quality grab samples compared with flow weighted composited samples depends strongly on the frequency of sampling (Fig. 5). Even with the sampling interval as short as 10 minutes, differences as high as 10% may appear.

On the basis of present investigations it is found that runoff flow should be sampled as early as possible. Cases with maximal concentration were observed already 10 minutes after the beginning of the water flow. However, it is not always true that pollutants concentrations reveal maximum at the start of the water flow and then decrease. Different concentration dynamics were observed. Results of the present paper are useful for water management planning in urban area.

List of Notation

$\overline{C_a}$	is average concentration;
c_i	is concentration in time i;
c_{i+1}	is concentrations in time $i+1$;
n	is number of measurements / observations.
Y_i^{obs}	is the ith observation for the constituent being evaluated
Y_i^{sim}	is the ith simulated value for the constituent being evaluated
Y^{mean}	is the mean of observed data for the constituent being evaluated
$W_{i-(i+1)}$	is water flow between in times i, $i+1$;
W	is total water flow during measurements.

Appendix A

Table A1. *List of indicators and methods used for estimation of concentrations in water.*

Nr	Substance	Method	Upper limits	Unit
1	1,2-dichloroethane	DKE_PGE	3	μg/l
2	Monobasic phenolic	STJ nr.U12	0.1	mg/l
3	Dibasic phenol	STJ nr.U12	15	mg/l
4	Ag	ISO 11885:1999	0.2	mg/l
5	a-Hexachlorocyclohexane	ISO 6468	1	μg/l
6	Aldrin	EN ISO 6468	0.05	μg/l
7	AOX	ISO 9562	1	mg/l
8	As	ISO 11885:1999	0.2	mg/l
9	BOD7	ISO 5815-1,2	15	mgO_2/l
10	Cd	ISO 11885:1999	0.2	mg/l
11	CN-	ISO 6703/1	0.2	mg/l
12	Cr	ISO 11885:1999	0.5	mg/l
13	Cu	ISO 11885:1999	2	mg/l
14	Dieldrin	EN ISO 6468	0.05	μg/l
15	Endrin	EN ISO 6468	0.05	μg/l
16	F-	ISO 10359/1	3	mg/l
17	g-Hexachlorocyclohexane	ISO 6468	2	μg/l
18	Hexachlorobenzene	EN ISO 6468	5	μg/l
19	Hexachlorobutadiene	EVS-EN ISO 10301	1	mg/l
20	Hg	EVS EN 1483	0.05	mg/l
21	Suspended solids (mineral, organic, VSS)	ISO 11923		
25	Isodrin	STJ nr.U63	0.002	mg/l
26	Chloroform	EVS-EN ISO 10301	1	mg/l
27	Oil	EVS-EN ISO 9377-2	5	mg/l
28	Ni	ISO 11885:1999	1	mg/l
29	Nitrogen (total), Kj.	SFS 5505		
30	p,p´-DDD	ISO 6468	0.05**	mg/l
31	p,p´-DDE	ISO 6468		
32	p,p´-DDT	ISO 6468		
33	PAH (sum)	STJ nr.U65	0.01	mg/l
34	Pb	ISO 11885:1999	0.5	mg/l
35	PCB (sum)	ISO 6468	0.05	μg/l
36	pH	ISO 10523	< 6; > 9	
37	Phosphorus (total)	EVS-EN ISO 6878		
38	Sb	ISO 11885:1999	0.5	mg/l
39	Sn	ISO 11885:1999	0.5	mg/l
40	Zn	ISO 11885:1999	2	mg/l
41	Tetrachloroethene	EVS-EN ISO 10301	-	
42	Carbon tetrachloride	EVS-EN ISO 10301		
43	Trichloroethene	EVS-EN ISO 10301	-	
44	Trichloromethane	EVS-EN ISO 10301	1	mg/l

**Upper limit for ´-DDD; p,p´-DDE and p,p´-DDT is summed up value

Acknowledgements

This work was supported by the Target Research Theme (SF0140072s08) and institutional research funding IUT (IUT19-17) of the Estonian Ministry of Education and Research. The authors acknowledge the help provided by the late Dr. Ain Lääne in the preparation of experimental studies.

Tiit Koppel, professor, Department of Mechanics, Tallinn University of Technology, Tallinn, Estonia

References

[1] Andresmaa E, Sedman P, Raia, T and Lääne A (2005) Proovivõtt reo- ja heitveest, sademeveest ning saastunud pinnasest. *Eesti Keskkonnaministeerium* (In Estonian).

[2] APWA (1969) *Water Pollution Aspects of Urban Runoff*. American Public Works Association. U.S. Department of the Interior, Federal Water Pollution Control Administration WP-20-15.

[3] Bach PM, Rauch W, Mikkelsen PS, McCarthy, DT, Deletic A (2014) A critical review of integrated urban water modelling – urban drainage and beyond. *Environmental Modelling & Software*, 54, pp. 88-107.

[4] Barbosa AE, Fernandes JN and David LM (2012) Key issues for sustainable urban stormwater management. *Water Research*, doi:10.1016/j.watres.2012.05.029.

[5] DE (2002) *How to Do Stormwater Sampling*. A guide for industrial facilities. Department of Ecology, Washington State, USA.

[6] Dotto CBS, Mannina G, Kleidorfer M, Vezzaro L, Henrichs M, McCarthy DT, Freni, G, Rauch W and Deletic A (2012) Comparison of different uncertainty techniques in urban stormwater quantity and quality modelling. *Water Research*, 46, 2545-2558.

[7] Dotto CBS, Kleidorfer M, Deletic A, Rauch W, McCarthy DT (2014) Impacts of measured data uncertainty on urban stormwater models. Journal of Hydrology, 508, pp. 28-42.

[8] Durrans R (2003) *Stormwater conveyance modelling and design*. Haestad Press.

[9] Elliott AH and Trowsdale SA (2007) A review of models for low impact urban stormwater drainage. *Environmental Modelling and Software*, 22 (3), 394–405.

[10] EMHI (2013) *Eesti Meteoroloogia- ja Hüdroloogia Instituut*. http://www.emhi.ee/ (In Estonian).

[11] Eriksson E, Baun A, Scholes L, Ledin A, Ahlman S, Revitt M, Noutsopoulos C and Mikkelsen PS (2007) Selected stormwater priority pollutants – a European perspective. *Science of the Total Environment*, 383, 41-51.

[12] Fletcher TD, Andrieu H and Hamel P (2014) Understanding, management and modelling of urban hydrology and its consequences for receiving waters: a state of the art. *Advances in Water Resources* 51, pp. 261-279.

[13] Gasperi J, Zgheib S, Cladiere M, Rocher V, Moilleron R and Chebbo G (2011) Priority pollutants in urban stormwater: Part 2 – Case of combined sewers. *Water Research*, doi:10.1016/j.watres.2011.09.041.

[14] Gupta HV, Sorooshian S and Yapo PO (1999) Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *J. Hydrologic Eng.* 4 (2), pp. 135-143.

[15] Huber WC and Dickinson RE (1992) Storm water management model, version 4: User’s manual, U.S. Environmental Protection Agency, EPA/600/3-88/001a.

[16] Koppel T, Suurkask V, Vassiljev A, Laanearu J and Puust R (2008) Tallinn stromwater-system investrigations (Tallinna sademevee uuringute teostamine). Report by Tallinn University of Technology, contract 8019 with *SWECO Projekt AS* (*In Estonian).*

[17] Laanearu J, Annus I, Vassiljev A and Koppel T (2009) On determination of flow routes in a stormwater network using the least squares method. *In: Integrating Water Systems: Computing and Control in the Water Industry* (J. Boxall & C. Maksimovic, ed.). Taylor & Francis, pp. 731 - 734.

[18] Laanearu J, Vassiljev A and Davies PA, (2011) Hydraulic modelling of stratified bi-directional flow in a river mouth. *Proceedings of the Institution of Civil Engineers: Engineering and Computational Mechanics*. 164 (4), pp. 207-216.

[19] Lee JG, Selvakumar A, Alvi K, Riverson J, Zhen JX, Shoemaker L and Lai F (2012) A watershed-scale design optimization model for stormwater best management practices. *Environmental Modelling & Software*, 37, 6-18.

[20] Lee H, Swamikannu X, Radulescu D, Kim SJ and Stenstrom MK (2007) Design of stormwater monitoring programs. *Water Research*, 41, 4186-4196.

[21] Martin QW (1983) Optimal Operation of Multiple Reservoir Systems. *Journal of Water Resources Planning and Management*, ASCE 109 (1), 58-74.

[22] ME (1971) *Storm Water Management Model Volume I*. Final Report, U.S. Environmental Protection Agency, Metcalf and Eddy, Inc. 11024DOC07/71.

[23] Moriasi DN, Arnold JG, Van Liew MW, Bingner RL, Harmel RD, Veith TL (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, 50 (3), pp. 885-900.

[24] Nash JE and Sutcliffe JV (1970) River flow forecasting through conceptual models: Part 1. A discussion of principles. *J. Hydrology*,10 (3), pp. 282-290.

[25] Pitt RE and Amy G (1973) Toxic Material Analysis of Street Surface Contaminants, U.S. Environmental Protection Agency, EPA-R2-73-283.

[26] Rossman LA (2009) Storm Water Management Model User’s Manual Version 5.0. EPA/600/R-05/040, National Risk Management Research Laboratory. United States Environmental Protection Agency, Cincinnati, Ohio.

[27] RT (2001) *Heitvee veekogusse või pinnasesse juhtimise kord*. Accounting Act. Riigi Teataja, I 2001, 69, 424. https://www.riigiteataja.ee/akt/13290813 (In Estonian).

[28] Sartor JD and Boyd GB (1972) Water Pollution Aspects of Street Surface Contaminants, U.S. Environmental Protection Agency, EPA R2-72-081.

[29] Sun S and Bertrand-Krajewski JL (2012) On calibration data selection: The case of stormwater quality regression models. *Environmental Modelling & Software*, 35, 61-73.

[30] Sutherland RC and Jelen SL (2003) Stormwater Quality Modeling Improvements Needed for SWMM. In: *Practical Modeling of Urban Water Systems Monograph 11* (W. James, ed.). CHI Publications, pp. 253-289.

[31] Zgheib S, Moilleron R and Chebbo G (2012) Priority pollutants in urban stormwater: Part 1 – Case of separate storm sewers. *Water Research*, doi:10.1016/j.watres.2011.12.012.

[32] Zoppou C (2001) Review of urban storm water models. *Environmental Modelling and Software*, 16 (3), 195–231.

[33] Tallinn (2012) Strategy of Tallinn City stormwater management until 2030 (Tallinna sademevee strateegia aastani 2030), http://www.tallinn.ee/g2914s60445 (In Estonian).

[34] USEPA (1992) *NPDES Storm Water Sampling Guidance Document*. US EPA, USA.

[35] Vassiljev A (2006) Comparison of Two One-Dimensional Nitrogen Leaching Models at the Watershed Scale. *Environmental Engineering Science*, 23 (1), pp 225-229.