MODELING URBAN STORMWATER RUNOFF POLLUTION IN TALLINN, ESTONIA

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ABSTRACT

This study presents an improved method for estimating the flow and pollution loading of the separate stormwater system of Tallinn, Estonia using the USEPA Stormwater Management Model (SWMM). In 2004 the city water company, AS Tallinna Vesi, reported that 6,344,793 m^3 of urban stormwater carrying 90.7 tons of total suspended solids (TSS) was discharged into the environment. In reality the stormwater amounts and pollution loads are not measured but are calculated using a formula based on drainage area and annual rainfall. A modeling method which incorporates measured flow and pollutant concentration data will provide a more comprehensive estimation of annual flow and pollution loading. A 940 ha portion of the Lasnamäe district of Tallinn was selected for study. Results indicate 2,751,631 m^3 of stormwater flow, 153 tons of total suspended solids (TSS), 8.5 tons of total nitrogen (TN) and 0.65 tons of total phosphorus (TP) were discharged to the Baltic Sea from the Lasnamäe district in 2004. These amounts are greater than previously reported. These results indicate the need for further study of urban stormwater pollution in Estonia and the need to develop methods for the reduction of stormwater pollution export to the Baltic Sea.

Key words: non-point source pollution; urban runoff quality, modelling, storm water management, SWMM

1. INTRODUCTION

The first urban drainage systems were built thousands of years ago to prevent flooding by transporting rainwater away from settlements (Burian, 1999). More recently, it has been recognized that urban stormwater has significant impact on receiving water qua1ity. Urban stormwater runoff has been identified as a significant source of pollution to estuaries, lakes and rivers in United States (USEPA, 2002). The U.S. has implemented legislation (CWA 1987, CZARA 1990) to reduce urban stormwater pollution through research, education and regulation. The European Union (CEC, 2002), the Helsinki Commission (HELCOM, 2002) and the Estonian government (EGR, 2001) have also implemented legislation to reduce urban stormwater pollution.

Over the past 15 years Estonia has focused attention on updating and renovating industrial and municipal wastewater collection and treatment systems (UN ESC, 2001). The upgrade of industrial technology, construction of new wastewater treatment facilities and decrease in agriculture has reduced the discharge of nitrogen by 73% and phosphorus by 79% between the late 1980s and 1999 (Pachel, 2002). Agricultural land use has been identified as a source of stormwater runoff pollution in Estonia (Iital et al, 2003) but the water quality impact of urban land use has yet to be determined. The ecological treatment of stormwater has not received much attention and is not widely practiced in Estonia.

Hydrologic modeling is a key component to stormwater management (Smith et al. 2005). SWMM is among the most widely used urban water quality and quantity simulation models (Vassilios and Rizwan 1997). SWMM was developed in 1969-1971 and was one of the first models to analyze the quantity and quality problems associated with urban runoff (Metcalf and Eddy, 1971). SWMM 5 was used in this study for the simulation of one year (1 January 2004 to 1 January 2005) of stormwater flow and pollution export from the Lasnamäe district of Tallinn, Estonia.

2. STUDY AREA

Estonia lies in the northern part of the temperate climate zone and in the transition zone between maritime and continental climate. The average annual temperature in Estonia is 4.5° C. The average temperature in February, the coldest month of the year, is -5.2 °C. The average temperature in July, which is considered the warmest month of the year, is 17 °C. Estonia typically experiences 160 to 180 days of precipitation per year of which 101 are days of snow (Jaagus, 2000). Snow cover usually lasts from mid-December to late March.

Tallinn, located at 59°26'N, 24°45'E is the capital city and the main seaport of Estonia. The population of Tallinn is 400,320 and the population density is 2,524 per km². Tallinn is located on Estonia's north coast, 80 kilometers south of Helsinki. The climate is characterized by a fairly cold winter, a cool spring with little precipitation, a moderately warm summer and a long and rainy autumn.

The area serviced by the stormwater system of Tallinn is approximately 6,500 hectares (Vaabel and Kandler 2001) but is expected to increase as the city expands and new pipes are installed in older areas lacking a stormwater network. The city center has a combined sewer system, while the other parts have mostly separate sewer systems. The Lasnamäe district of Tallinn is a densely populated urban area housing approximately 115,000 residents. It is also the largest separate stormwater system in Tallinn. The portion of the Lasnamäe district which was selected for study is connected to a separate stormwater sewer system that discharges into Tallinn Bay near the Lauluvaljak song festival grounds. The area serviced by this portion of the Lasnamäe stormwater network is approximately 940 ha, which is about 14 % of the whole system. The land use within the catchment is mostly high density residential with approximately 28% impervious area. The original land cover of the study area was an alvar, or limestone plain, with thin soil (5-25 cm) and sparse vegetation. Urban development within the area during the 1980s has changed much of the original soil.

3. MATERIAL AND METHODS

One-minute precipitation data from a Nivus tipping bucket rain gauge located approximately 5 km from the study area were used for calibration and verification of storms occurring between 12 May 2006 and 24 May 2006. These precipitation data were provided by AS Tallinna Vesi. One-hour precipitation data were from the Tallinn (Harku) meteorological station located approximately 40 km from the study site were also used for calibration, verification and long term simulation. These data were provided by the Estonian Meteorological and Hydrological Institute (EMHI). The stormwater system data for the Lasnamäe study area was provided by AS Tallinna Vesi in digital format. These data include the location and elevation of all stormwater pipes and manholes, pipe diameter, pipe material, and year constructed. The Lasnamäe study network consists of 5,547 manholes and 5,263 pipes that range from 50 mm to 2,560 mm in diameter and have a total length of 120.49 km. A simplified network of 1102 pipes with diameter $\geq$ to 500 mm was selected for use in this study. The total length of pipes in the simplified study network was 43.06 km (Fig 1).

Figure 1. Simplified version of the Lasnamäe study area stormwater network.

The 940 ha drainage area was determined using a 1-m resolution digital elevation map (DEM) provided by AS Tallinna Vesi. This area was divided into 296 sub-catchments ranging in size from 0.31 ha to 11.35 ha. The sub-catchments were assembled into 26 sub-catchment groups ranging in size from 11.1 ha to 101.0 ha that correspond with the major collector branches of the network.

Impervious area was determined for each sub-catchment group from 1:10,000 scale land use maps provided by the Estonian Land Board. Areas indicated as buildings, roofs, and pavement were determined to be impervious area. Areas indicated as forest, brush, field/garden, grass land, pasture, lawn and bog were determined to be pervious area. The total impervious area (TIA) within the study site was determined to be approximately 28 %. In order to correct for the large amount of impervious area not directly connected to the stormwater network the effective impervious area (EIA) for the study site was determined to be 7.2 % using the equation EIA=0.004 (TIA)1.7 (Sutherland, 1995). Percent slope was determined for each sub-catchment group using a 1-m resolution DEM and the slope function of the ERDAS Imagine computer software. The width of each sub-catchment was determined as a function of the area of the sub-catchment. Each sub-catchment was assumed to be square in shape and the width was determined as the distance from the edge of the square to a point in the center (representing the stormwater sewer inlet) using the formula $W = 0.5*\sqrt{area}$, where W= width (m) and area = sub-catchment area (m^2). Width was determined for each subcatchment and percent imperviousness and percent slope were determined for each sub-catchment group.

On 20 September 2005 AS Tallinna Vesi and Tallinn Technical University began a stormwater monitoring program to measure stormwater discharge and pollution concentration from the Lasnamäe district. AS Tallinna Vesi installed a Nivus PCM3 flow meter in a 2,560 mm stormwater collector pipe within the Lauluvaljak song festival grounds. This collector pipe is part of the Lasnamäe stormwater system and is approximately 630 m from its outlet to Tallinn Bay. The Nivus PCM3 uses an ultrasonic Doppler flow velocity and pressure depth sensor along with channel geometry to calculate flow in the channel. Five-minute flow data were used to calibrate and validate the flow portion of the model.

Time weighted stormwater samples were collected using an Edmund Buhler PB-MoS water sampler provided by the Institute of Environmental Engineering at Tallinn Technical University. Within 24 hours of collection, samples were brought to the water quality laboratory of the Institute of Environmental Engineering at Tallinn Technical University and immediately analyzed for TSS, TN and TP or held at 4°C. TSS concentration was determined using a gravimetric filtration method. To analyze for TN, samples were digested with peroxodisulphate, after which the concentrations of nitrate were determined using a photospectormeter. TP was analyzed using the peroxodisulphate digestion procedure to convert the various forms of phosphorus into dissolved orthophosphate after which the concentrations of nitrate were determined using a photospectormeter. SWMM employs a modified Manning's equation for calculation of surface runoff. In this study the kinematic wave routing method with a five-minute time step was selected for calculation of runoff transport through the sewer network. The flow portion of the model was calibrated by adjusting selected parameters to

	Range *	Selected
Impervious Area Parameters		
•% Impervious	± 10 %	100.0
•Inperv D-Stor (mm)	0.3 - 2.5	0.15
•n Inperv	0.010 - 0.015	0.01
Catchment Parameters		
•Width (m)	± 30 %	100
•Slope (%)	± 30 %	100
Pervious Area Parameters		
•Perv D-Stor (mm)	2.45 - 7.62	7
•n Perv	0.02 - 0.45	0.25
•Perv area with Zero D-Stor (%)		35
Network Parameters		
•n Pipe	0.011 - 0.013	0.011
Horton Infiltration Parameters		
•Max Infil (mm)	25-75	27.5
•Min Infil (mm)	0-10	0.28
•Decay Constant (1/hours)	2-7	0.41
•Drying Time (days)	2-14	14

* Temprano et al, 2006

Table 1. Flow and infiltration calibration parameters

achieve a satisfactory match for peak flow rate and total volume for selected storms. The Horton equation was selected to determine infiltration from pervious surfaces. Using flow data from a large (38.6 mm) storm occurring 14 November 2005 infiltration parameters were adjusted to provide a satisfactory hydrograph fit (Table 1).

Dry Weather Flow and Pollutant Concentrations were determined based on measurements gathered during dry weather flow conditions. Base flow was determined to be 42 l/s and the dry weather concentrations of TSS, TN and TP were determined to be 5.0 mg/l, 3.0 mg/l and 0.075 mg/l respectively. Based on these estimates the annual base flow pollutant load for TSS, TN and TP is 6.62 tons, 3.97 tons and 0.10 tons respectively. The exponential function was selected for TSS build-up/wash-off. Concentrations of TN and TP were determined as a co-fraction of TSS concentration. The co-fractions for TN and TP were determined to be 0.25% and 0.22% respectively. An exponential build-up/wash-off function was also used to simulate the first flush effect seen in TN and TP concentrations. The build-up/wash-off parameters for TSS, TN and TP are listed in Table 2. Pollutant build-up is based on land use, antecedent dry days and accumulation factors. Pollutant wash-off is based on land use, storm flow and removal factors. Based on impervious area, 28 % of the study site was determined to contribute pollutants from "Urban" land use.

Build-Up	TSS	TN	TP
•Max Build-	25	0.15	0.25
•C	1	0.0015	0.0025
Wash-Off			
•Coefficient	4.9	250	500
•Exponent	1.57	1.0	2.35

Table 2. Pollutant calibration parameters

The flow portion of the model was calibrated using data from three storms (Fig 2, Table 3). Flow volume and peak discharge were verified using data from 6 storms (Fig 3, Table 4).

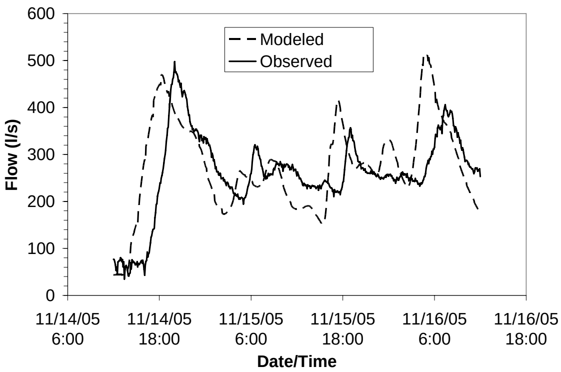

Figure 2. Flow calibration, 14 November 2005.

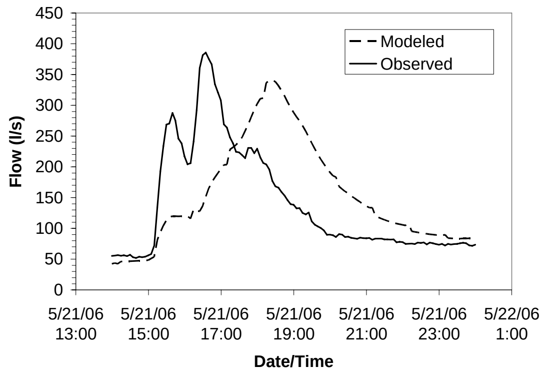

Figure 3. Flow verification, 21 May 2006.

		Flow Volume (m^3)		Peak Flow (l/s)	
	Precip.(mm)	Observed	Modelled	Observed	Modelled
2 Oct. 2005	2.9	5,177	5,186	227.3	143.7
14 Nov 2005	36.8	45,084	47,683	498.0	514.3
19 May 2006	2.1	2,934	2,730	75.9	63.3

Table 3. Observed and modelled flow volume and peak flow used in model calibration.

		Flow Volume (m^3)		Peak Flow (l/s)	
	Precip.(mm)	Observed	Modelled	Observed	Modelled
28 Sept. 2005	3.1	4,401	3,250	247.8	161.3
29 Sept 2005	4.8	6,743	6,962	357.7	251.5
6 Nov 2005	4.0	4,298	3,691	217.8	190.2
20 May 2006	1.8	3,404	2,822	132.0	100.8
21 May 2006	7.5	5,103	5,627	385.5	341.0

Table 4. Observed and modelled flow volume and peak flow used in model verification.

The concentration and volume of TSS, TN and TP were calibrated using data from one storm occurring on 19 May 2006 (Fig 4, Table 5). The concentration and volume of TSS, TN and TP were verified using data from one storm occurring on 21 May 2006 (Fig 5, Table 5). Differences in the modelled and observed hydrographs can be attributed to the large size and inhomogeneous nature of the study area. Within the study area are green corridors containing soils with high infiltration rates as well as large buildings and roads directly connected to the stormwater network.

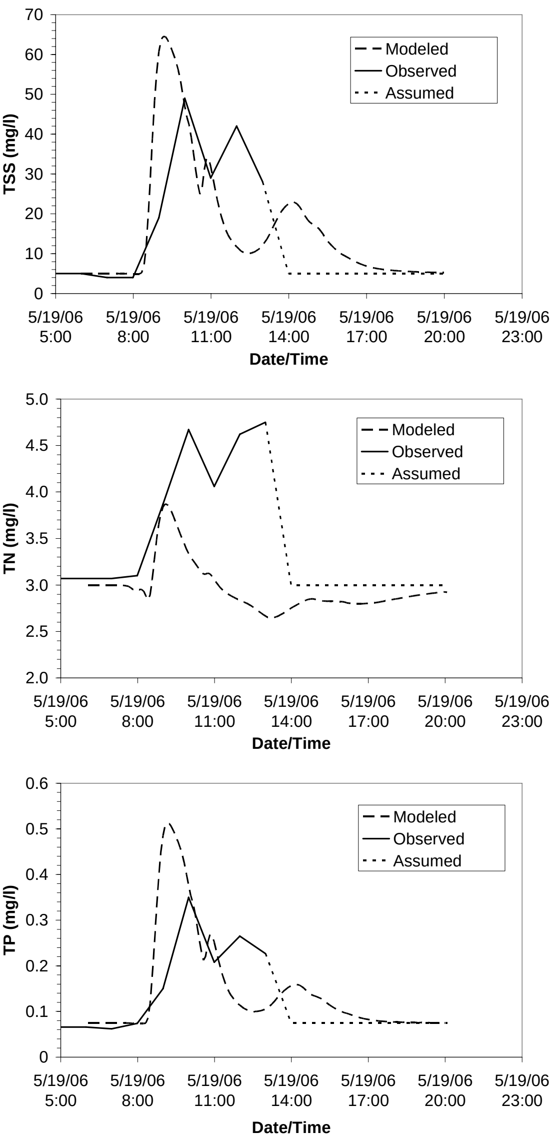

Figure 4. Pollutant calibration, 19 May 2006

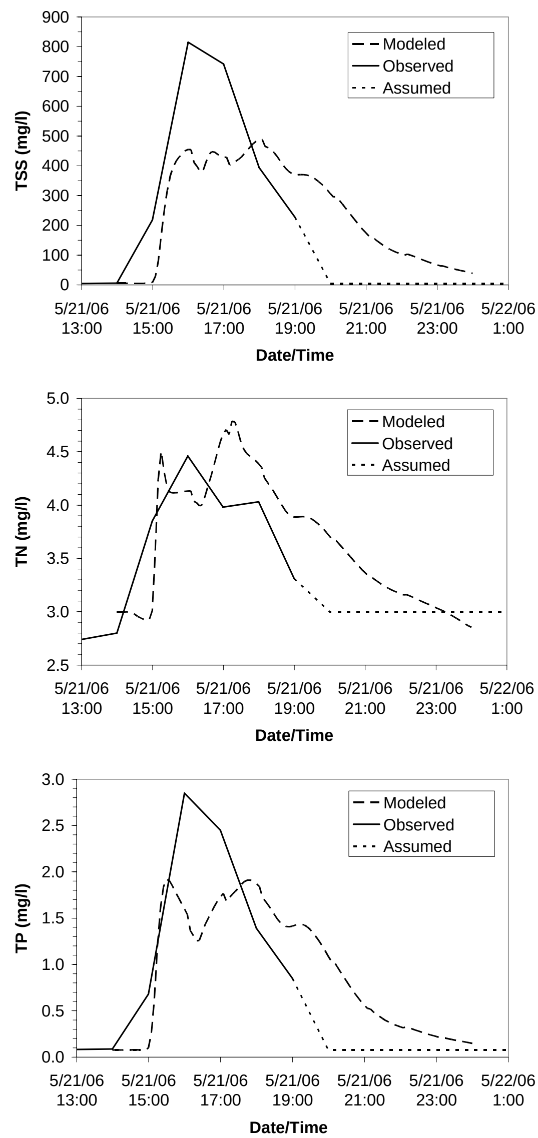

Figure 5. Pollutant verification 21 May 2006

	TSS (kg)		TN (kg)		TP (kg)	
	Observed	Modelled	Observed	Modelled	Observed	Modelled
19 May 2006	48.2	47.7	11.1	8.1	0.4	0.4
21 May 2006	2,054	1,792	20.2	21.7	6.9	6.7

Table 5. Observed and modelled pollutant loads used in model calibration (19 May 2006) and verification (21 May 2006).

In cold-climate regions snowmelt can contribute to flooding, combined sewer overflow (Thorolfsson, 1999) and pollutant loading (Marsalek et al. 2003). The effect of snowmelt on stormwater quantity and quality were not addressed in this modeling study but data gathered during a 28 March 2006 snow melt event indicate high concentrations of pollutants including TSS, nutrients, chloride and sulfate as well as heavy metals (Table 6). The high observed concentrations of cadmium may be caused by the atmospheric deposition of jet fuel emissions and the close proximity of the study area to Tallinn Airport.

Pollutant	Peak (mg/l)	Total (kg/day)
TSS (mg/l)	1376	17,894
TN (mg/l)	8.87	186
TP (mg/l)	3.11	45
Cl^- (mg/l)	886	12,763
SO_4^{2-} (mg/l)	73	1,148
Pb (µg/l)	1.41	0.039
Cd (µg/l)	0.12	0.001
Cu (µg/l)	5.34	0.086
Zn (µg/l)	51.00	0.757
Cr (µg/l)	1.59	0.030
Ni (µg/l)	2.37	0.045
Fe (µg/l)	44.00	0.499

Table 6. Peak concentration and daily loading of pollutants from a 28 March 2006 snow melt event.

4. RESULTS

The SWMM model was run for the time period 1 January 2004 to 1 January 2005 during which 804.8 mm of precipitation occurred. It was found that 2,751,631 m^3 of flow occurred during this one year period carrying 153 tons TSS, 8.5 tons TN and 0.56 tons TP to Tallinn Bay. SWMM model results indicate annual loadings of TSS, TN and TP greater than those indicated in previous studies of urban stormwater pollution in Tallinn (Table 7). The Estonian Environmental Research Center (EERC) provides annual stormwater pollution loading estimates for the same Lasnamäe network based on data gathered over a five year period (2000–2005). The SWMM model predicts 80 % greater annual flow than the EERC study. The lower annual flow prediction of the EERC study may be the result of flow measurements made during dry weather conditions. The lower annual flow of the EERC study may also explain the lower TSS and TP annual loadings. The AS Tallinna Vesi study provides an estimate of annual flow and TSS loading for the stormwater network of all of Tallinn. The annual flow estimated by the AS Tallinna Vesi study seems low when compared to the SWMM study which considers only 14% of the stormwater network of Tallinn. The AS Tallinna Vesi estimates of annual stormwater pollution loading are calculated using a formula based on drainage area and annual rainfall. The lower flow estimates of the AS Tallinna Vesi study may be a result of a smaller estimate of catchbasin size. The lower pollutant loading estimates may be the result of the use of baseflow pollutant concentrations in annual loading calculations.

	SWMM (Lasnamäe, 2004)	EERC (Lasnamäe, 2000-2005)	AS Tallinna Vesi (All of Tallinn, 2004)
Flow (m^3/yr)	2,751,631	1,530,000	6,344,793
TSS (tons/yr)	153.0	12.0	90.7
TN (tons/yr)	8.5	8.0	
TP (tons/yr)	0.56	0.2	

Table 7. Comparison of SWMM model results with other estimates of urban stormwater pollution in Tallinn, Estonia.

5. CONCLUSIONS

This study presents an improved method for the calculation of stormwater flow and pollution loading from the Lasnamäe district of Tallinn, Estonia. Measured flow and pollutant concentrations were used to calibrate and verify the SWMM model for this purpose. Results indicate a greater annual loading of TSS, TN and TP than previously reported. The limited number of water samples collected for pollutant calibration/verification creates incomplete polutograps (Fig 4-5). Base flow concentrations of pollutants were used to complete the polutographs for model calibration/verification. The water quality data used in model calibration/verification represent a limited range of seasonal and precipitation depth conditions. Additional data is needed for improved model accuracy. This study indicates the need for further research of urban stormwater pollution in Estonia and the need to develop methods to reduce pollution export to the Baltic Sea. In addition further study is needed to determine the effect of snow melt on urban stormwater pollution loading in Estonia.

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