Urban Flood Modeling of a Partially Separated and Combined Drainage System in the Grefsen Basin in Oslo, Norway

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Abstract

The Storm Water Management Model (SWMM) has been globally used for stormwater management. However, the calibration and evaluation of SWMM for historical rainfall–runoff events in partially separated and combined drainage systems is rarely reported in Norway. In this study, we employed SWMM for the Grefsen catchment in Oslo, Norway. The main problem in the Grefsen basin is combined sewer overflow. We calibrated the model parameters based on 32 rainfall–runoff events and evaluated the calibrations using four indicators: Nash–Sutcliffe efficiency, percentage bias, and continuity errors for runoff and flow. There were 32 successful calibrations using Nash–Sutcliffe efficiency, 30 successful calibrations using percentage bias, 32 successful calibrations using continuity error runoff, and four successful calibrations using continuity error flow. SWMM can well simulate the dynamics of hydrological and hydraulic systems in this catchment. Among the 124 validations, there were 88 successful simulations using Nash–Sutcliffe efficiency, 35 successful simulations using percentage bias, 124 successful simulations using continuity error for runoff, and 62 successful simulations using continuity error for flow. The results show that percentage bias and continuity error flow are the critical indicators for model calibration. This study reveals the large uncertainty caused by calibration and validation criteria, and highlights the importance of considering model computation error.

1 Introduction

Urbanization is a global trend. Since 2009, more than 50% of the world population has been living in urban or semiurban areas according to *World Population Prospects 2019* from the United Nations (2019). By the year 2030, the urban population will exceed 80% of the total world population (Salvadore et al. 2015). In developed countries, the degree of urbanization is even higher. For example, approximately 87% of the population in Sweden (Statista 2019) and 82% in Norway (SSB 2018) are already living in urban areas.

One major problem of urbanization is the increasing magnitude and frequency of urban flooding. Impermeable surfaces reduce infiltration and increase flow velocity. With climate change, especially increases in storm intensity and other extreme events, urban flooding increases and economic damages and other consequences become severe (Nie et al. 2009; Velasco et al. 2012).

Urban flooding is a great threat to the security of residents and causes huge economic loss. In Norway, the main problem of urban flooding is basement flooding (Lindholm et al. 2006; Nie 2016). In Oslo, insurance claims for urban flood-related damages, mainly basement flooding, from 2008 to 2014 were >97 million NOK (VAV 2016) and approximately 30% of the damage events

are additionally not claimed (Finsland 2019). Urban flooding is a major route for transporting urban pollutants to rivers and oceans (Nie et al. 2011; Åstebøl and Hvitved-Jacobsen 2006).

Combined sewer overflow (CSO) is another threat to the urban environment and ecosystem. A combined sewer system (CSS) is quite common in many countries and cities (Salvadore et al. 2015). In Oslo, the sewer system is 2250 km in total, and >36% of the sewer system is CSS (Holmberg 2019). The excess flow, containing untreated sewage, discharges directly into streams and other water bodies. CSO may include high levels of toxic chemicals and destroy the local ecosystem. In the United States, 860 communities have combined sewer systems, serving about 40 million people (Wikipedia 2021) and there are currently about 800 CSO outfalls in New York State (Department of Environmental Conservation 2021).

Urban hydrological modeling is a useful and important tool for urban flood simulation, protection and management. In recent years, modeling tools have improved significantly due to the development of computation techniques and the availability of high-resolution data. However, there is no universal methodology for urban hydrological modeling at the catchment scale due to the great heterogeneity of urban areas and the multiplicity of interactions between the urban structure and the water system (Li et al. 2020, Salvadore et al. 2015, Skaugen et al. 2020). The

Storm Water Management Model (SWMM; Rossman 2015) and the Model for Urban Sewers (MOUSE; Lindberg et al. 1986) are the most widely used models for stormwater management and urban drainage planning. SWMM is more often used for scientific purposes than MOUSE because it is open source software and is free for use worldwide. SWMM provides a good balance between the level of detail required to describe physical processes and computational parsimony (Niazi et al. 2017). However, applications of the model in Norway are rarely reported in international scientific journals because the MOUSE model has a major market share in Norway. Existing literature is limited to the use of SWMM to reproduce rainfall–runoff for grey and green roofs and to transfer parameters among different sites (Johannessen et al. 2019; Hamouz and Muthanna 2019; Russwurm et al. 2018). The main purpose of this paper is to examine for the first time the application of SWMM in a Norwegian urban catchment to simulate historical events. Figure 1 gives an overview of the workflow.

Figure 1 Flowchart of this study.

2 Study area and data

2.1 Study area

Oslo is the capital city of Norway and the country's economic and governmental center. Grefsen is a residential area in the northern part of Oslo. The Grefsen catchment is approximately 1.3 km² (Figure 2) with a population of ~5000 inhabitants. Impermeable surfaces, mainly buildings and roads, account for 22% of the catchment area. The eastern part of the catchment is flat and densely built up, and most residents live there.

The sewer networks in the study catchment contain both separated and combined systems. The combined sewage system covers the southwest of the catchment and the separated sewage system covers the northeast of the catchment. The CSOs occur at the outfall, weir AKS2 at inspection chamber 161143 as identified in the archives of Oslo Water and Sewage Agency. A stormwater weir is at the side of the combined weir. When the water depth in the combined weir exceeds 40 cm, sewage overflows through the stormwater pipes into the Akerselva River. In 2017, CSOs lasted for a total of 5 h 23 min (Storteig 2019).

Figure 2 Location of Grefsen catchment and the outfall: (a) location of Norway and Oslo; (b) location of the Grefsen catchment in urban Oslo; (c) location of the outfall; (d) digital elevation model and the sewage system, where wastewater pipes partly overlap with stormwater pipes.

2.2 Data

The data requirements of SWMM vary according to the model processes and setup. For example, the temperature is required for the calculation of snowmelt and evaporation but is not necessary for short term flood simulation. In this study, we simulated discharge at an outfall for 32 rainfall–runoff events in three years, 2010, 2016 and 2017. The longest duration event lasted only ~2 d and therefore evapotranspiration was not important. Thus we used only rainfall data as climate inputs. Other types of data including information about the drainage system and hydrological characteristics of the subcatchments were necessary inputs. Discharge measurements at outfall AKS2 were used for model calibration.

Rainfall data were measured at the Kjelsås rain gauge. The rain gauge was a NIVUS RM 202 (Nivus 2015) pluviometer. The rain gauge recorded the time when 0.1 mm precipitation was detected. The raw data were aggregated to a time step of 5 min.

The discharge was calculated according to velocity and depth, which were measured by automatic sensors and an ASS FlowShark Triton flow monitor. The accuracy of the discharge was dependent on the accuracy of velocity and depth measurements. Sometimes, waste adheres to the sensors and causes discharge disturbances, mainly in low flow periods.

The data for hydraulic inputs, junctions and conduits were obtained from the Oslo Municipality Water and Sewage Administration.

The surface characteristics of the subcatchment included elevation, slope, and percentage of impermeable surface. The source of elevation was a digital map at a spatial resolution of 0.5 m. It was a hybrid product of two terrain data sets. For the Oslo city area, the terrain map was extracted from lidar data obtained in the summer of 2014 (Mæhlum 2014). For the forest and hilly area surrounding the city area, the terrain was interpolated from elevation contours from the Norwegian Mapping Authority.

The impermeable surface was a combination of land surface type images and local maps. The land surface type image was classified using the Sentinel-2 satellite data (Stange 2017) as shown in Figure 3. The spatial resolution was 10 m. This spatial resolution cannot represent small roads or buildings, so roads and buildings from the Norwegian common map database (FKB; Norwegian Mapping Authority 2005) were integrated. The satellite land surface type map and the FKB road and building maps were resampled by the nearest neighbor method to 0.5 m raster data and eventually rasterized.

Figure 3 Land surface including roads, buildings and land surface classification from the Sentinel-2 satellite.

3 Methods

3.1 SWMM

The Storm Water Management Model (SWMM) is a combined hydrologic (rainfall–runoff) and hydraulic (pipe routing) model (Lager et al. 1971; Digiano and Mangarella 1975; Rossman 2015).

In the hydrological module of SWMM, the hydrological response unit is the subcatchment, which is further divided into three types of subareas: pervious, impervious with depression storage, and impervious without depression storage. The three subareas share the same subcatchment characteristics and

inputs, such as slope, width, and precipitation and evaporation rates. Runoff generation occurs independently in each subarea, but areas can route into each other before all runoff reaches the same subcatchment outlet.

In terms of hydrological processes, SWMM can simulate the processes of evaporation, rainfall–runoff, snowmelt, and groundwater flow. For the sewerage system, SWMM offers several types of nodes and links according to the modeling objective. The nodes represent point objects in the sewage system (e.g. access chambers, junctions between channels, and weirs). The links represent connections between nodes (e.g. pipes and channels). Three methods are available for flow routing in the links: steady flow, kinematic wave, and dynamic wave. More information about SWMM is available from the webpage <https://www.epa.gov/water-research/storm-water-management-model-swmm>.

Equations and parameters

There are many equations and parameters in SWMM. Here we give a detailed description of the overland flow because it is important for sustainable stormwater management and the parameters are very sensitive to discharge.

SWMM conceptualizes a subcatchment as a rectangle with uniform slope S and width W . The water depth d of the subcatchment is a function of rainfall input and discharge output.

$$\frac{\partial d}{\partial t} = i - e - f - q \quad (1)$$

where:

- t = time,
- i = rate of rainfall plus snowmelt,
- e = surface evaporation rate,
- f = infiltration rate, and
- q = runoff rate.

Assuming the overland flow across the subcatchment surface is uniform, the Manning equation can be used to express the runoff volumetric rate Q as:

$$Q = \frac{1}{n} S^{1/2} R_x^{2/3} A_x \quad (2)$$

where:

- Q = discharge from subcatchment,
- n = surface roughness coefficient,
- S = subcatchment slope,
- A_x = area of discharge cross section, $A_x = W(d - d_s)$,
- R_x = hydraulic radius, $R_x = d - d_s$, and
- W = subcatchment width,
- d = overland flow depth,
- d_s = depression storage depth,
- A = subcatchment area.

The runoff flow rate per unit of surface area q is described by:

$$q = \frac{1}{A \cdot n} W S^{1/2} (d - d_s)^{5/3} \quad (3)$$

The variables are as defined above. For details, see Rossman and Huber (2016).

3.2 Catchment delineation

The catchment is the area in which hydrological processes occur. The delineation of the catchment boundary is usually based on the terrain. However, the terrain is significantly changed by human activities in urban areas, so it is necessary to use a high-resolution digital elevation model of the urban area to represent terrain as modified by urban infrastructure. The sewage system affects water to flow through the subcatchment. It collects surface runoff into the subsurface pipe system, transports the water to downstream recipients or wastewater treatment plants (WWTP). The flow follows the pipe rather than the terrain. Therefore, it is important to be careful in delineating the catchment boundary.

We delineated the area of the catchment to outfall AK52 based on a 0.5 m lidar terrain model using a multiflow direction algorithm that diverts the water flow downstream in proportion to the slopes of all the downstream cells created by the software Geographic Resources Analysis Support System (GRASS) GIS, version 7.4.1. Additionally, we manually checked to see if the sewage system imported or exported runoff across the catchment boundary.

3.3 Subcatchment delineation

To run SWMM, the catchment was further divided into subcatchments. Normally surface runoff ends in a street drain where it enters the piped drainage system. However, street drains were not identified in the drainage system descriptions. Therefore the outlets of the stormwater subcatchments were assigned to their nearest stormwater or combined access chambers by the nearest neighbor method. The subcatchments were aggregated according to the pipe system to reduce computing demand. Subcatchments having the same downstream access chambers were merged as big subcatchments. Aggregation began at the smallest subcatchment and continued until all the subcatchments that shared the same outlet were aggregated into one big subcatchment. Eventually, there were nine subcatchments.

Runoff components

Outfall AK52 is a combined access chamber and discharge measurements included wastewater and stormwater runoff as well as groundwater leakage. We modeled only stormwater runoff and therefore wastewater and groundwater components were removed from the observed discharge to calibrate SWMM.

Groundwater and wastewater consist of dry period discharge. Groundwater leakage is a relatively stable runoff component and does not fluctuate because of rainfall or water drainage. We assumed the daily minimum discharge of dry periods to be the magnitude of groundwater. For days without data, groundwater was linearly interpolated from other days with data.

Wastewater discharge is the remaining component of the dry period flow. The wastewater time series were aggregated into

patterns: monthly, daily, hourly and weekend. The wastewater time series were generated according to the SWMM method: Inflow = (Average Value) × (Pattern 1, monthly) × (Pattern 2, daily) × (Pattern 3, hourly or weekend). The average value was calculated from the SSB municipal water supply (2019) and the population in the study area.

3.4 Model calibration and evaluation criteria

Model calibration was performed using the SRCT tool in PCSWMM (2020). SRCT can run SWMM in parallel with defined parameter uncertainties and find parameter sensitivities (PCSWMM 2020). The user has to verify the model to get the true model efficiency. It is common to run the SRTC tool several times to achieve a good calibration. The goodness of calibration can be judged by a visual comparison of the measurement data and the modeling results, or by numerical indicators. In this study, the most reliable measurements were the discharge data at the outfall AK52. We used two numerical indicators, Nash–Sutcliffe efficiency (*NSE*) and percentage bias (*PB*). We adopted $NSE > 0.5$ and $PB < 25\%$, which were used as criteria for the acceptable model performance of urban runoff simulations by Johannessen et al. (2019). Additionally, continuity errors (*CE*) in the model computation were used as additional indicators for both the hydrology (*CE* runoff) and hydraulics (*CE* flow). The continuity errors are not conventional calibration indicators, but they are dependent on the model parameters. The model user has to make sure that the continuity errors are in an acceptable range, which indicates SWMM is stable. According to Farah (2009), a 10% continuity error is tolerable, both for *CE* runoff and *CE* flow, and we adopted these values as our criteria. The equations of the indicators are:

$$NSE = 1 - \frac{\sum_{t=1}^T (Q_m^t - Q_0^t)^2}{\sum_{t=1}^T (Q_0^t - \bar{Q}_0)^2} \quad (4)$$

where:

Q_m = the modeled runoff series
 Q_0 = the observed runoff series

$$PB = \frac{\sum_{t=1}^T (Q_m^t - Q_0^t)}{\sum_{t=1}^T Q_0^t} \times 100 \quad (5)$$

where:

Q_m = the modeled runoff series
 Q_0 = the observed runoff series

$$CE = 100 \times \left(1 - \frac{\text{total output water}}{\text{total input water}} \right) \quad (6)$$

4 Results

4.1 Rainfall–runoff events

In total, there were 32 rainfall–runoff events (Table 1) available for model evaluation. SWMM was calibrated using every event so there were 32 calibrations. There were 14 events in 2010, 16

events in 2016, and 2 events in 2017. There were 9 events in June, 8 events in July, 12 events in August, and 3 events in September. The average duration of the events was 11.5 h; event duration ranged from 135 min to 3150 min. The maximum rainfall ranged from 0.4 mm/5 min to 5.2 mm/5 min.

Table 1 Events overview.

Name	Start	end	Mean <i>P</i> (mm/h)	max <i>P</i> (mm/h)	mean <i>Q</i> (L/s)	max <i>Q</i> (L/s)	duration (min)
event01_1	20100608T124000	20100608T175000	0.99	4.80	41.77	90	310
event01_2	20100608T191000	20100609T012000	1.06	26.40	45.73	150	370
event02	20100609T120500	20100609T154500	8.37	45.60	289.11	1030	220
event03_m	20100610T213000	20100613T020000	1.07	12.00	77.91	880	3150
event04_2	20100630T080000	20100630T160500	1.54	12.00	47.14	120	485
event05	20100712T222500	20100713T022500	3.67	62.40	99.59	490	240
event06_1	20100729T070000	20100729T161000	0.48	7.20	23.33	40	550
event06_2	20100729T161500	20100731T043000	0.91	26.40	47.20	160	2175
event07_1	20100805T133500	20100805T212500	1.31	36.00	37.37	140	470
event07_2	20100806T000000	20100806T021500	2.40	48.00	51.43	160	135
event07_3	20100806T025500	20100806T181000	0.76	14.40	44.46	170	915
event08	20100813T045000	20100813T213500	1.23	31.20	49.34	160	1050
event09	20100913T204500	20100915T045000	0.83	24.00	36.37	130	1925
event10	20100924T084500	20100925T033500	1.62	9.60	82.25	160	1130
event12_m	20160615T201500	20160616T022000	0.44	10.80	71.35	160	365
event14_m1	20160620T123000	20160621T043500	1.14	6.00	72.16	160	965
event14_m2	20160621T044000	20160621T072000	1.75	15.60	125.94	450	160
event16	20160627T210500	20160628T045000	0.52	6.00	55.76	110	420
event18_1	20160701T115500	20160701T210500	0.61	15.60	61.62	140	550
event18_2	20160702T084500	20160703T012500	0.65	20.40	75.57	280	1000
event21_m1	20160712T163500	20160712T201500	1.12	13.20	64.00	150	220
event21_m2	20160714T160500	20160714T215500	0.56	12.00	72.68	180	350
event22	20160728T002000	20160728T054000	0.63	15.60	69.08	210	320
event24	20160803T154500	20160804T130500	0.88	14.40	72.72	310	1280
event25	20160805T031000	20160805T114500	0.70	19.20	80.96	240	515
event26_1	20160806T030000	20160806T073500	0.94	12.00	70.71	130	275
event26_2	20160806T084500	20160806T191500	0.83	9.60	112.52	230	630
event26_3	20160807T134500	20160807T210500	0.66	4.80	63.93	110	440
event32	20160820T222500	20160821T011500	4.18	22.80	94.29	460	170
event33	20160826T005500	20160826T100000	0.92	10.80	94.00	270	545
event38_1	20170809T000000	20170809T075000	1.40	15.60	46.74	140	470
event41	20170909T163000	20170909T195500	2.91	22.80	320.00	840	205

There was a high correlation between mean event rainfall and maximum discharge but a low correlation between maximum rainfall and maximum discharge (Table 2). The results show, not unexpectedly, that the total amount of rainfall during an event is more important than the peak rainfall.

Table 2 Pearson correlations between events maximum discharge (max *Q*) and mean rainfall (mean *P*) and maximum rainfall (max *P*).

	Mean <i>P</i>	Max <i>P</i>
max <i>Q</i>	0.72	0.37

4.2 Runoff components

Sewage is only a small component of the total discharge, but it is the pollutant source of the CSO problem. Figure 4 shows the hourly pattern of wastewater discharge. Sewage has a clear hourly pattern within the day. It increases from midnight to

early morning and then decreases, and increases again in the afternoon. There is more wastewater flow on workdays than on weekends. Sewage on weekends is more stable than on workdays after the early morning.

Figure 4 Hourly patterns of wastewater for the workweek (Monday–Friday) and weekend (Saturday and Sunday).

Sewage is a relatively stable component of the total discharge, but it is the source of pollutants. Figure 5 shows the elapsed time of overflow, total discharge, and sewage for the CSO events. There were good linear relationships between the elapsed time and the square root of sewage volume (Pearson correlation 0.95), and elapsed time and the square root of discharge volume (Pearson correlation 0.97) for CSO. The correlation between the square root of sewage volume and the square root of total discharge was 0.99:

$$\sqrt[3]{Q/100} = 0.05636 \times \text{time} + 0.19854 \quad (7)$$

$$\sqrt[3]{W} = 0.05462 \times \text{time} + 0.12346 \quad (8)$$

$$\sqrt[3]{W} = 0.97556 \times \sqrt[3]{Q/100} - 0.07605 \quad (9)$$

Figure 5 Relation between elapsed CSO time and sewage (*W*), and elapsed CSO time and total discharge (*Q*); CSO occurs when *Q* > 200 L/s; red dot = total discharge, black dot = sewage.

4.3 Calibration

We calibrated the SWMM model for each rainfall–runoff event and validated the calibrations using the four indicators *NSE*, *PB*, *CE* runoff and *CE* flow. The calibrations were quite successful in terms of hydrological and hydraulic dynamics, indicated by high *NSE* and low *PB* (Figure 6). In terms of computation performance, the values of *CE* runoff were very low, with all calibrations <1%. However, *CE* flow is a critical indicator and only four calibrations were <10%. The numbers of successful calibrations according to each criterion are tabulated in Table 3.

Figure 6 Histograms of the criteria for calibrations: (a) *NSE*; (b) *PB*; (c) *CE* runoff; (d) *CE* flow.

Table 3 Number of successful calibrations out of a total of 32 calibrations for each indicator.

<i>NSE</i>	<i>PB</i>	<i>CE</i> runoff	<i>CE</i> flow
32	30	32	4

Table 4 shows the model performance of the four calibration criteria and Figure 7 shows the hydrographs. The calibration for event3 was the best in terms of *NSE*, *PB* and *CE* flow. The calibration for event12_m was the worst in terms of *NSE*, *PB* and *CE* runoff.

Table 4 Model performance of the successful calibrations.

Event	<i>NSE</i>	<i>PB</i> (%)	<i>CE</i> runoff (%)	<i>CE</i> flow (%)
event10	0.871	−8.52	−0.003	−7.285
event12_m	0.705	15.10	−0.036	7.664
event14_m1	0.862	−8.78	−0.006	−8.557
event33	0.938	−6.24	−0.013	6.665

Figure 7 Hydrograph of the successful calibrations; black line = observed, red line = simulated.

4.4 Validation

Each successfully calibrated SWMM model was validated on the other 31 events. There were therefore 124 (4 successful calibrations × 31 validations) validation model runs altogether. The four indicators were calculated for every validation. Figure 8 shows the values of the indicators for the validations. Table 5 shows the number of successful validations based on the four criteria. Values of *CE* runoff for all the validations are within ±10%. *NSE*, *PB* and *CE* flow filter out the successful validations. For model calibration, *PB* and *CE* flow were found to be the most critical indicators.

Figure 8 Model performance of the validations: (a) NSE; (b) PB; (c) CE runoff; (d) CE flow.

Table 5 Number of successful validations for each indicator.

Event	NSE	PB	CE runoff	CE flow
event10	23	11	31	4
event12_m	19	9	31	31
event14_m1	20	8	31	8
event33	26	7	31	19
Total	88	35	124	62

Among the 13 successful validations, two were calibrated using event10, nine using event12_m, and two were calibrated using event33 (Table 6). The calibration using event14_m1 was not successfully validated. It was difficult to determine why event12_m performed best in the validation. Figure 7 shows that the hydrograph of event12_m was the simplest, and there was one peak. Event10 had two similar close peaks; event33 had two peaks, one very small and the other large. Event14_m1 had three peaks that were very close to each other.

Table 6 Successful validations.

Cal_event	Val_event	NSE	PB (%)	CE runoff (%)	CE flow (%)
event10	event02	0.625	3.9	-0.1	-6.9
event10	event03_m	0.674	-19.3	0.0	-3.5
event12_m	event03_m	0.623	21.1	0.0	0.4
event12_m	event14_m1	0.895	3.0	0.0	1.2
event12_m	event16	0.625	18.2	0.0	5.6
event12_m	event18_1	0.687	24.9	0.0	3.7
event12_m	event18_2	0.693	18.5	0.0	2.0
event12_m	event21_m2	0.838	-16.3	0.0	6.4
event12_m	event25	0.887	-7.9	0.0	3.4
event12_m	event26_2	0.745	-9.8	0.0	2.5
event12_m	event33	0.793	-17.7	0.0	2.6
event33	event25	0.606	-2.0	0.0	9.5
event33	event26_2	0.865	8.6	0.0	6.0

Notes: Cal_event: calibration event; Val_event: validation event.

4.5 Parameters

PCSWMM had 56 parameters. We found that 18 parameters affected discharge at the AK52 outfall. Figures 9 through 11 show the calibrated parameters. The most sensitive parameters were those for subcatchment characteristics: area, width, slope, and impermeable percentage. It was difficult to quantify them precisely due to interactions and interdependencies between parameters. For example, a small area can have a large impermeable surface percentage and small infiltration capacity. Although these parameters have clear physical interpretations, they cannot be estimated from measurements. Our experience tells us that it is necessary to calibrate them to get a satisfactory model performance.

The infiltration parameter K_{sat} (conductivity) was very small compared to measured values, varying from 80 mm/h to 4160 mm/h (Storteig 2019). The was because our model did not include groundwater, and therefore infiltrated water did not contribute to total discharge at the outfall. The total discharge was largely controlled by the subcatchment area and the percentage impervious area. Infiltration had little effect in this model and infiltration parameters depended greatly on the subcatchment parameters.

The length of the calibration period ranged from 135 min to 3150 min. The shortest event only had 27 data points with which to calibrate the model. In Figure 9 and Figure 10, many calibrated parameters were still at their initial value (1 in the figures); for example, permeable area roughness and permeable area storage. These parameters were not sensitive to discharge simulation. Besides, there was no strong correlation (only 0.09) between *NSE* of calibration and calibration period length, and there was no strong correlation between model performance in calibration periods and the lengths of validation periods.

Figure 9 Violin plots of calibrated subcatchment and subarea parameters; the characteristics are for each

of the subcatchments; for the subcatchment, the plot presents the ratio of the calibrated value to the initial value estimated from the input data, so 1 indicates that the calibrated value was the same as the initial value; for the subarea, the plot presents the parameter value; red dot = successful calibration.

Figure 10 Violin plots of calibrated pipe and infiltration parameters; for the pipe, the plot presents the ratio of the calibrated value to the initial value estimated from the input data; for the infiltration, the plot presents the parameter value; red dot = successful calibration.

Figure 11 Violin plots of calibrated section (Geom1) and outfall (Elevation) parameters; the plot presents the parameter value; red dot = successful calibration.

5 Conclusions

We investigated the applicability of the Storm Water Management Model (SWMM) in a partially separated and partially combined sewer system in the Grefsen catchment in Oslo. We examined parameter sensitivity, the relation between calibration period and performance, and the relation between calibration period length and validation. We calibrated SWMM using 32 events and evaluated the model performance using four indicators: Nash–Sutcliffe efficiency, percentage bias, continuity error for runoff, and continuity error for flow. The number of successful calibrations varied greatly for the different indicators. There were 32 successful calibrations out of 32 using *NSE*, 30 successful calibrations using *PB*, 32 using *CE* runoff, and 4 using *CE* flow. There were only 4 successful calibrations using all four indicators.

Of the 124 (4×31) validations, 88 were successful using *NSE*, 35 using *PE*, 124 using *CE* runoff, and 62 using *CE* flow. There were 13 successful validations using all four indicators. The results show large uncertainty due to the calibration and evaluation indicators and highlight the importance of considering model computation error for flow routing when using SWMM.

It is difficult to generalize model parameters due to the uncertainty in discharge measurements and in the sewer network as well as the high heterogeneity among events. More research, including measurements and model experiments, is necessary to assess the performance of this Norwegian urban water system.

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