Control strategies minimizing wastewater overflow in Oslo

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Abstract

As climate change intensifies storms, larger rainwater volumes load the sewage network systems above the design capacity and escalate the risk of combined sewer wastewater overflow to natural waterways. Accordingly, the control challenge is to prevent the combined sewer overflow by adjusting the manipulated variables, such as pumps and gates, in the sewage network system. The aim of this study is to (1) compare traditional and predictive control strategies to four different storm scenarios, and to (2) quantify the preventive effect of these control strategies on wastewater overflow. The case study is applied in the Oslo combined sewage network system. Control strategies applying feedforward strategy minimize the overflow within the constraints of the sewer infrastructure. Compared to no control, applying feedforward-feedback control strategy decreases overflow to natural water ways by 21- 88% in different rain scenarios. Compared to feedback control strategy, the feedforward-feedback strategy can decrease overflow by 3--9%.

1. Introduction

As climate change intensifies storms, larger rainwater volumes load the sewage network systems above the design capacity and escalate the risk of combined sewer wastewater overflow to natural waterways. Accordingly, the control challenge is to prevent the combined sewer overflow by adjusting the manipulated variables in the sewage network system.

Most urban water systems are controlled by passive control, rule based local control or manual operation in order to minimize overflow to natural waterways and optimize energy consumption for pumping [1]. In manually controlled combined sewer systems, heavy rain can easily lead to overflows if preventive manual actions are not taken prior to and during the rain event. In order to minimize the combined sewer overflow, research in different real time control algorithms has gained strong interest during the past decade. Real time control uses sensors and controllers, and an automation system with supervisory control and data acquisition. The controllers convert real-time measurements into operational decisions by rules and algorithms of varying complexity [1].

Most of the advanced control applications to combined sewer systems have been implemented in simulation environment. For example, Schuetze and Alex [2] have used Simba model of the Astlingen sewer network in Germany to quantify the combined sewer overflow volume of the during a year using different control strategies. Their findings confirm that MPC would provide the minimal volume close between the base case and the theoretical optimum for the Astlingen sewer system [2]. A model-based approach on estimation and model predictive control of the wastewater levels in the Oslo sewer network tunnel basins has been proposed by [3].

So far, only a few industrial implementations of real-time control have been presented, due to insufficient instrumentation of the sewer network. Model predictive control has been applied to utilize the water storage capacity of the sewer network to minimize costs of pumping during varying electricity prices in Denmark [4].

In this study model-based control is applied to the Oslo combined sewage network system. Oslo metropolitan area with its surrounding municipalities host more than one million citizens and the region receives approximately 1010 mm precipitation (rain) each year. Despite continuous improvements on the infrastructure of the sewer system, storm events exert a considerable pressure on the city's urban drainage system and combined sewer overflows to the Oslo fjord occasionally. The overflow of diluted, untreated wastewater-rainwater mixture affect negatively the marine life and water quality at beaches along the Oslo Fjord. The aim was to (1) compare traditional and predictive control strategies to four different storm scenarios, and to (2) quantify the preventive effect of these control strategies on wastewater overflow. Research question: Which control strategies can minimize overflow of diluted wastewater during heavy rain?

2. Materials and Methods

2.1. Materials

This study uses a high-fidelity MIKE simulator of the Oslo urban drainage system for the data collection. DHI has developed and calibrated the dynamic simulator as part of the Future City Flow EU-project. Simplified modeling, control strategy development and testing were done in Matlab/Simulink.

2.2. Methods

Modeling: High-fidelity MIKE model is used to collect data of historical rain scenarios in the Oslo sewage network. The MIKE+ data was used to develop and calibrate the simplified model consisting of ordinary differential equations and algebraic equations. The simplified model was implemented in Matlab/Simulink.

Control: The ordinary differential equations were linearized and Laplace-transformed to transfer function models. The transfer function models were used for parametrization and tuning the MPC and the PID controllers. The control algorithms were tested in Matlab/Simulink environment using the ordinary differential equations. ODE23t solver was used for all scenarios and controllers. Due to late data access, control algorithm testing in MIKE+ software was not possible.

2.3. Symbols

Symbols used in equations are given in Table *1*.

Table 1: List of symbols

Symbol	Description	Unit
A	Catchment area	m^2
B	Magazine bottom area	m^2
F	Flowrate	m^3/min
i	Catchment i	-
I	Imperviousness	%
j	Pipeline j	-
m	Magazine m	-
PE	Person equivalent	-
R	Rain fall	mm/min
t_D	Transport delay in pipeline or magazine	min
θ	Catchment area delay	min
		-

2.4. System description

The combined sewer network in Oslo and the surrounding municipalities stretches over 108 catchment areas. In this study, based on geography, these areas were combined into 9 catchments with estimated average characterization given in Table 2. The characterization of the catchments is based on data from the MIKE+ model. The water from the catchment areas is led to a network sewer tunnels that transport the water to two separate water resource recovery facilities, Veas in the west side of Oslo and Bekkelaget in the east side of Oslo.

Table 2: Catchments areas in the Oslo metropolitan sewer network with tunnel inlet point, estimated person equivalent PE, area A, imperviousness I and delay θ.

Inlet	Catchment	PE [10^3]	A [$10^6 m^2$]	I [%]	θ [min]
I1	Festning	150	77	11,7	28,6
I2	Østensjø	125	77	9,77	28,6
I2	Furuset	150	115	7,81	42,9
I3	Torshov	150	115	7,81	42,9
I4	Nordstrand	125	77	9,77	28,6
I2	Lillestrøm+	181	415,8	2,62	154
I5	Bærum	135	192	4,22	71
I6	AskerLier	130	192	4,06	71
I5	SkiOppegård	65	192	2,03	71

2.5. Data collection and case scenarios

Four historical rain events were chosen for this study, case 1 and 2 with heavy storm, case 3 with extremely heavy storm and case 4 with moderate rain. The length of each case scenario is four days (96h) in order to let the combined sewer system settle back to the dry conditions after the rain event. The periods selected have dry weather during the first day, rain during the second day and dry weather during the third and fourth day, as presented in Figure 1. A summary of the rain scenarios in the Oslo combined sewer network is given in Table 3.

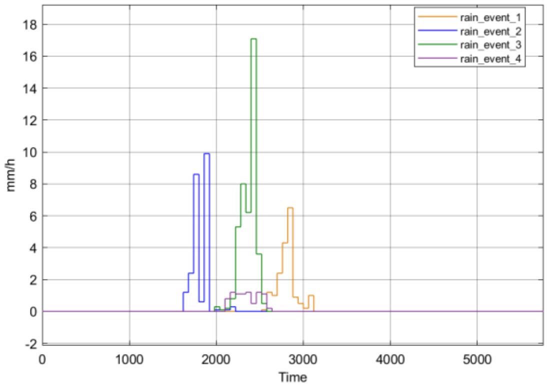

Figure 1: Rain fall during case scenarios.

Table 3: Characterization of case scenarios with length of 96 hours.

Case	Rain start time [dd:mm:yy]	Rain fall [mm]	Rain duration [h]
1	11.06.19 19:00	18	9
2	29.08.19 04:00	22,7	5
3	09.08.17 10:00	41,5	7
4	09.05.16 12.00	8,2	8

3. Modeling

The modelling of the Oslo sewer network consists of four sub-models. The first sub-model is between rainfall and sewer network inlet. The second sub-model provides continuous municipal wastewater flow with sinusoidal diurnal pattern to the inlet of the sewer network. The third sub-model consist of the main tunnels in the sewer network. The sewer tunnel network is approximated as 13 links (transport delay) and 5 magazines with storage volume and a final control element (pump or gate). The fourth sub-model is the overflow accumulator in the magazines. In the simplified Matlab/Simulink model (Figure 2), every catchment area has only one inlet to a tunnel in the sewer network. The tunnel network leads water to the water resource recovery facilities. Parts of the tunnels are used to store a fixed volume of water during heavy rains. The storage capacity in the tunnels is modeled as magazines with finite volumes. The water flow through the magazines is controlled with a pump or a gate. If the maximum level limit in the magazine is reached, overflow is directed to natural waterways.

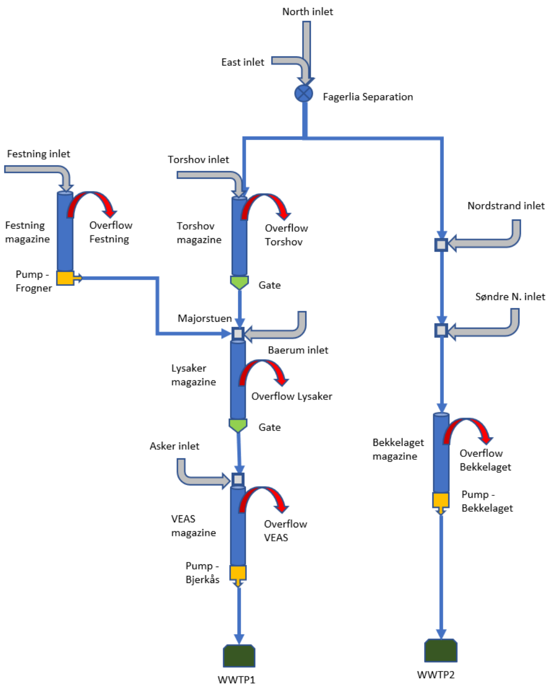

Figure 2: Simplified model of the combined sewage network in Oslo area.

The inlet boundaries of the model are the flowrates from the six catchment areas. The flowrate from catchment area *i* to the tunnel inlet $F_{inlet,i}$ is estimated as a sum of the municipal wastewater flow $F_{mun,i}$ and the rain induced water flow $F_{rain,i}$.

$$F_{inlet,i} = F_{mun,i} + F_{rain,i} \quad (1)$$

The municipal wastewater flow is calculated based on population (person equivalent) in the area, person equivalent wastewater flow and the diurnal pattern (24h day-night variation). The person equivalent wastewater flow F_{PE} is assumed 0.0002005 m^3/min. The diurnal pattern is estimated as sinus curve with amplitude of 1, bias of 1 and angular frequency of 2π/(1440min), with zero value at 05:00 and maximum value of 2 at 17:00.

$$F_{mun,i} = F_{PE} \cdot PE_i \cdot \left(1 + sin\left(\frac{2\pi}{1440}t\right)\right) \quad (2)$$

The rain induced water flow from catchment area i is estimated as a product of rain intensity R_i, catchment area A_i and catchment imperviousness I_i , and delay θ between rain fall and rain induced flow at the tunnel inlet.

$$F_{rain,i} = R_i(t+\theta) \cdot 10^{-3} \cdot A_i \cdot I_i \quad (3)$$

The wastewater flow from tunnel inlets is gathered to the sewer tunnels. The tunnels are modeled as links and magazines. A link is modeled as a plug flow through the tunnel, a pure transport delay, given in Table 4. The flowrate through the link j is the flowrate in with a transport delay t_{Dj}:

$$F_{outlet,j} = F_{inlet,j}(t - t_{D,j}) \quad (4)$$

Table 4: Parameters of the tunnel/link models with inlet, outlet, length L and transport delay tD.

Link	from	to	L [km]	t_D [min]
L1	Festning inlet	Festning magazine - Majorstuen	4,4	44
L2	East inlet (Østensjø)	Fagerlia separation	3,5	35
L3	North inlet (Furuset)	Fagerlia separation	7,1	70
L4	Fagerlia separation	Torshov magazine - Majorstuen	7,3	72
L5	Torshov inlet	Torshov magazine - Majorstuen	3,0	30
L6	Majorstuen	Vaekerø	5,4	54
L7	Vaekerø	Lysaker magazine	7,6	75
L8	Baerum inlet	Lysaker magazine	6,0	59
L9	Lysaker magazine	VEAS magazine – WWTP1	15,0	149
L10	Asker inlet	VEAS magazine – WWTP1	8,0	79
L11	Fagerlia separation	Bekkelaget magazine – WWTP2	5,5	55
L12	Nordstrand inlet	Bekkelaget magazine – WWTP2	1,0	10
L13	Søndre N. inlet	Bekkelaget magazine – WWTP2	7,5	74

The Oslo sewer network model includes five magazines which are modelled as a pipeline with transport delay t_{Dm} and a vertical tank volume in the end. The parametrization of the magazines is given in Table 5. The plug flow through the pipeline part of the magazine feeds to the tank at the end of the magazine. The flow rates from different links (L) is summed together at the inlet of the magazine pipeline and plug flow with transport delay t_{Dm} is assumed along the magazine pipeline:

$$F_{inlet,m} = \sum F_{outlet,j}(t - t_{D,m}) \quad (5)$$

Water height in the vertical tank at the end of the magazine is modeled with a simple tank. The magazine tank has inlet at the top and outlet at the bottom with a pump at the exit line. The maximum water height in the vertical tank model is about 3 meters and the minimum water level is 0,1 m (to avoid numerical instabilities). The nominal dry weather level in the magazines is half of the maximum, about 1,5 m. The water height in the magazine is given as:

$$\frac{dh_m(t)}{dt} = \frac{1}{B}\left(F_{inlet,m}(t) - F_{outlet,m}(t)\right) \quad (6)$$

Each magazine has an overflow model that applies if the high-level limit is reached. The volume of the overflow water is calculated as accumulated sum.

Table 5: Parameters of the magazine models with max water height (H), bottom area (B) and nominal transport delay (t_D).

ID	Magazine	Link	H_{max} [m]	B [$10^3 m^2$]	t_D [min]
M1	Festning	L1	3	10,3	44
M2	Torshov	L4	3	17,2	72
M3	Lysaker	L7	3,35	19,9	75
M4	Bekkelaget	L11	3	12,9	55
M5	Veas	L9	3,35	39,4	149

The time delay tD for each link and magazine with length Lj is calculated based on estimated speed of flow through the tunnel. This estimate is based on the minimum flow velocity Vfmin=84.05 m/min, and the flow velocity difference Vfdif=33.6m/min between maximum flow velocity (117,7 m/min) and minimum flow velocity. The flow velocity difference is weighted with the hydrostatic ratio in the magazine, the water level H(t) in the magazine j divided by maximal water level Hmax.

$$t_{D,j} = \frac{L_j}{V_{f,min} + V_{f,dif} \cdot \left(H(t)_j / H_{max}\right)} \quad (7)$$

The final control element in each magazine is either a pump station (Frognerparken, Bjerke, Bekkelaget) or a gate (Torshov, Lysaker). It is assumed that the time dynamics of these are negligible, and thus they are represented with adjustable gain of 0-100% of the maximum outlet flowrate given in Table 6. The Fagerlia weir has position between 0,3-0,7 the nominal value is 0,5. The weir does not restrict the flowrate.

Table 6: Final control elements of the sewer network with minimum, nominal and maximum flowrates.

ID	Placement	F_{min} [m^3/min]	F_{nom} [m^3/min]	F_{max} [m^3/min]
M1	Festning (pump)	6	30	150
M2	Torshov (gate)	0	152	343
M3	Lysaker (gate)	0	266	638
M4	Bekkelaget (pump)	17	84	440
M5	Veas (pump)	32	159	660
F6	Fagerlia (weir)	0	-	-

In addition, wastewater from the catchment areas in North of Oslo can be divided at Fagerlia separation using a flow separation weir between west sewer system leading to Veas (WWTP1) and east sewer system leading to Bekkelaget (WWTP2).

The outlet boundary conditions of the model are the two water resource recovery plants, Veas at west and Bekkelaget at east, with parameters given in Table 7. The Bekkelaget capacity was increased by 50% in October 2021, but in the simulation model for all scenarios it is assumed that this capacity applies already in 2016.

Table 7: Water resource recovery facility with estimated capacities.

Name	P.E capacity	Normal flow in [m3/min]	Max flow in [m3/min]
Veas	793000	159	660
Bekkelaget	418000	83,8	440

4. Control strategy development and testing

4.1 Control strategy development

The control goal is to avoid overflow in the magazines. Three different control strategies were developed based on linearized transfer function models of the governing nonlinear equations. The five (5) controlled variables are the wastewater levels in the five magazines. The manipulated variables are three (3) pump stations, two (2) gates, and separation weir (1). The disturbance variables of the system are the six (6) lumped tunnel inlet flowrates.

Transfer functions

For the controller development purposes, the ordinary differential equations of the system between the controlled variables and manipulated variables were linearized and Laplace transformed. The first order transfer functions between the controlled variables and the manipulated variables are integrators with gain Kp, presented in Table *8*. The transfer functions in the magazine tanks were estimated with a delay τ_d of zero as the final control element is placed right at the outlet of the tank model. It is assumed that the Fagerlia flow separation weir has negligible time dynamics compared to the pumps and gates.

Table 8: Transfer functions between controlled variables (levels) and manipulated variables (pumps and gates).

TF	MV	CV	Kp [-]
TF1	Festning pump P_F	H_F	$-1/B_1$
TF2	Torshov gate G_T	H_T	$-172/B_2$
TF3	Lysaker gate G_L	H_L	$-319/B_3$
TF4	Bekkelaget pump P_B	H_B	$-1/B_4$
TF5	Veas pump P_V	H_V	$-1/B_5$

4.2 SISO control strategy development

As each magazine has one controlled variable (level) and one manipulated variable (pump station or weir), these were paired for the single-input single-output control strategy. Fagerlia separation weir has its own independent controller for allocating the northern inflow between the west and east sewer networks

The PI-controller parameters for the level controllers in the magazines were calculated based on the Skogestad IMC tuning [5] rules for integrating system. The transfer functions are given in Table *8*. The tuning parameter τ_c was chosen as 1 minute because the transfer functions did not include a delay. The controller gain at magazine j was calculated as:

$$K_{c,j} = \frac{1}{K_{p,j}(\tau_{c,j} + \tau_{d,j})} \quad (8)$$

The controller integral time at magazine j was calculated as:

$$T_{i,j} = 4 \cdot (\tau_{c,j} + \tau_{d,j}) \quad (9)$$

The PI-controller parameters are given in Table *9*.

Table 9: PI-control parameters for the final control elements at magazines.

ID	Description	TF	Kc	Ti [min]	Rate limiter [1/min]
M1	Festning (pump)	1	-10 367	4	±4,8
M2	Torshov (gate)	2	-100	4	±0,033
M3	Lysaker (gate)	3	-63	4	±0,033
M4	Bekkelaget (pump)	4	-39 466	4	±21
M5	Veas (pump)	5	-12 959	4	±14

Proportional control with the following relationship between water height at Torshov magazine $H_T(t)$ and Bekkelaget magazine $H_B(t)$ was applied to the flow separation weir at Fagerlia:

$$W_1(t) = 0{,}5 + 0{,}2\left(\frac{H_T(t)}{H_{T,max}} + \frac{H_B(t)}{H_{B,max}}\right) \quad (10)$$

4.3 MIMO control strategy development

Linear model predictive control was chosen as the multi input-multi output control algorithm due to its popularity in similar applications. The linear MPC tuning rules were adopted from [6] and [1]. The MPC controller was parametrized using the transfer functions between the controlled variables (levels) and the manipulated variables (pumps, gates and weir) given in Table *8*. The sampling time of the system was chosen 5 min. As the transfer functions of the integrating systems (magazines in Table *8*) do not have time constants, a model horizon N of 120 minutes was chosen. According to [6], the control horizon M was chosen to be half of N, 60 minutes. The collective horizon approach with equal control and prediction horizons, presented in [1] was the most used approach found in the literature review and adopted in this study. The prediction horizon P was therefore 60 minutes. The tuning parameter Q, weighting the importance of the five controlled variables, was chosen as identity matrix, because keeping the level under high limit is as important in every magazine. The tuning parameter R, penalizing changes in the manipulated variables was set to zero. The rate limiters of the PI-controllers (Table *9*) were implemented also as separate blocks for the control signals (outputs) of the model predictive controller.

4.4 Feedforward control strategy development

A feedforward control strategy was designed to maximize the available storage volume in the main tunnels of the combined sewer system. The strategy uses the weather forecast and lowers the water levels in the combined sewer tunnels to minimum before the anticipated rain event. In this study, the feedforward strategy was implemented as real-time optimization of controlled variable setpoints using rain forecast data. The nominal setpoints of the magazines water levels were 50% of the maximum level. Twelve hours prior to the forecasted rain event, the setpoints were lowered to 0,2 m for 28 hours, and then, lifted back up to nominal value.

4.5. Control strategy testing

The control results are illustrated for case 4. The precipitation data is presented in Figure *3*. The combined sewer inlet flowrates from the six lumped catchment areas are presented in Figure 4. The changes in the manipulated variables are shown in Figure 5 and the setpoint tracking of the controlled variables in Figure 6.

The results for total overflow with the difference control strategies compared to no control is given in Table *10*. Applying control strategies decrease the overflow as can be seen from Table *11* comparing overflow reduction between no-control strategy and the other control strategies. The maximal overflow reduction is about 0,6 million m^3, if the water levels in the combined sewer tunnels (magazines) are at its lowest when the rain starts.

Implementation of PI and MPC control strategies decrease the overflow by 40 % in heavy rain cases 1 and 2, and up to 80% for moderate rain case 4, whereas in extreme heavy rain case 3 the limitation of the buffer/storage capacity of the combined sewer system only allow overflow decrease of 16 %.

Both PI and MPC control strategies with forecast (lowering storage setpoint 12 hours prior to rain) improves the results compared to no-control result by 45 % in heavy rain cases 1 and 2, 88% in moderate rain case 4 and by 21 % in extremely heavy rain case 3.

Table 10: Total overflow in Mm^3 for case scenarios with different control strategies.

Case	No control	PI	PI+F	MPC	MPC+F
1	1,13	0,62	0,58	0,62	0,58
2	1,49	0,96	0,88	0,95	0,89
3	2,78	2,34	2,20	2,34	2,21
4	0,45	0,095	0,055	0,094	0,056

Table 11: Difference [Mm^3] in total overflow between no-control strategy and other control strategies.

Case	PI	PI+F	MPC	MPC+F
1	0,51	0,55	0,51	0,55
2	0,54	0,61	0,55	0,60
3	0,44	0,59	0,44	0,58
4	0,36	0,40	0,36	0,40

Table 12: Difference [%] in total overflow between no-control strategy and other control strategies.

Case	PI	PI+F	MPC	MPC+F
1	45	49	45	49
2	36	41	37	40
3	16	21	16	21
4	79	88	79	88

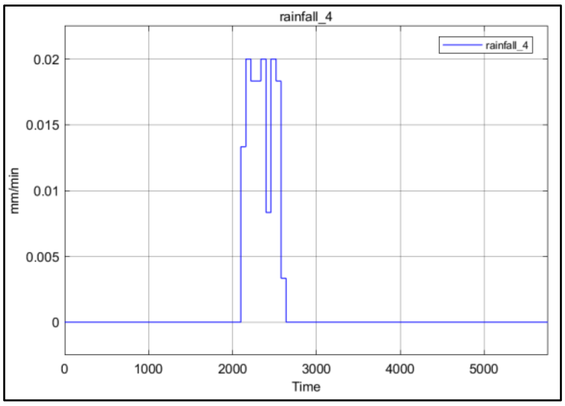

Figure 3: Rain event 4 with real precipitation measurement from Blindern weather station in Oslo.

5. Summary and Discussions

For all scenarios, real-time optimization using forecast data have significantly improved the performance of both PI and MPC control strategies. PI control with forecast has performed slightly better than MPC with forecast. Additionally, PI with forecast had lower pump loads than MPC with forecast.

Thus, the answer our research question is: Control strategies applying feedforward strategy will minimize the overflow within the constraints of the infrastructure. Compared to no control, applying feedforward control strategy that uses rain prediction, overflow to natural water ways can be decreased up to 88% in moderate rain scenario, up to 49% in heavy rain scenarios and up to 21% in extreme storm scenario. Compared to control strategy without feedforward strategy, the feedforward strategy can minimize overflow by 3--9%.

Due to late data access during the project, some assumptions in the combined sewer network model need to be updated. As our project partners have pointed out, some of the catchment areas (Lillestrøm, Lier, Ski and Oppegård), should be omitted as these deliver water to other water resource recovery facilities than Bekkelaget and Veas. As these four catchment areas produce only small flowrates to the current combined sewer model, it is assumed that the effect to the final results is minimal.

Future work is suggested on alternative SISO and MIMO controller parametrizations, new case studies on different rain events, and handling of uncertainties of rain events using advanced control strategies such as stochastic MPC using the Matlab model. Implementation of the best control algorithms should be implemented in the MIKE+ model and tested with different rain scenarios.

Acknowledgments
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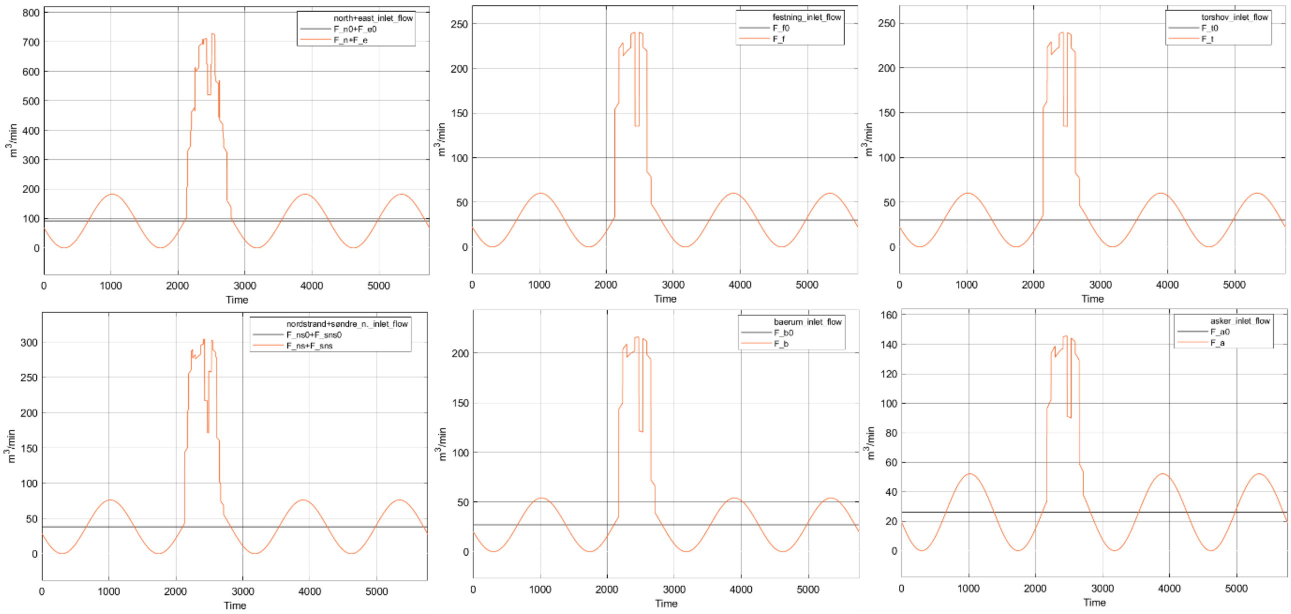

Figure 4: *Rain event 4 with combined sewer inlet flowrates I1 North+East; I2:Festning; I3: Torshov; I4: Nordstrand; I5:Bærum I6: Asker. The orange line presents the simulated sewer system inlet flowrate (combined municipal wastewater flow with diurnal pattern and rain event) around the average daily value of municipal wastewater flow indicated with black line.*

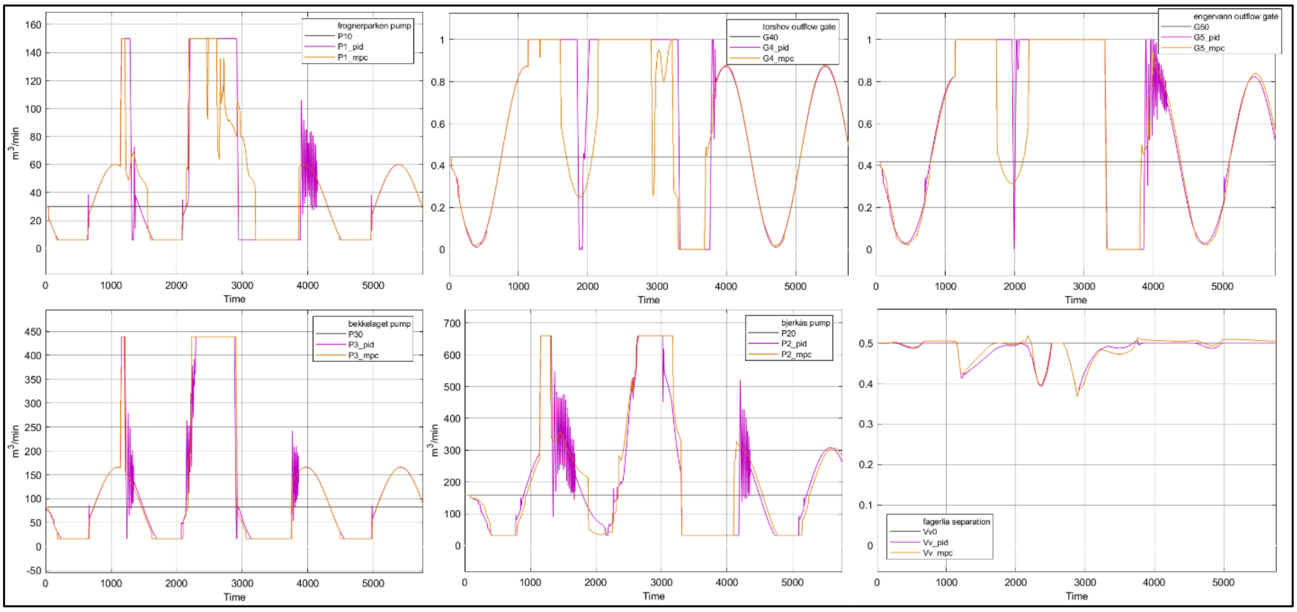

Figure 5: *Rain event 4 with changes in manipulated variables in Frognerparken magazine, Torshov magazine, Lysaker magazine, Bekkelaget magazine, Veas magazine and Fagerlia separation using the feedforward strategy combined with PI-controllers (magenta), MPC algorithms (yellow). The nominal MV value is indicated with black line.*

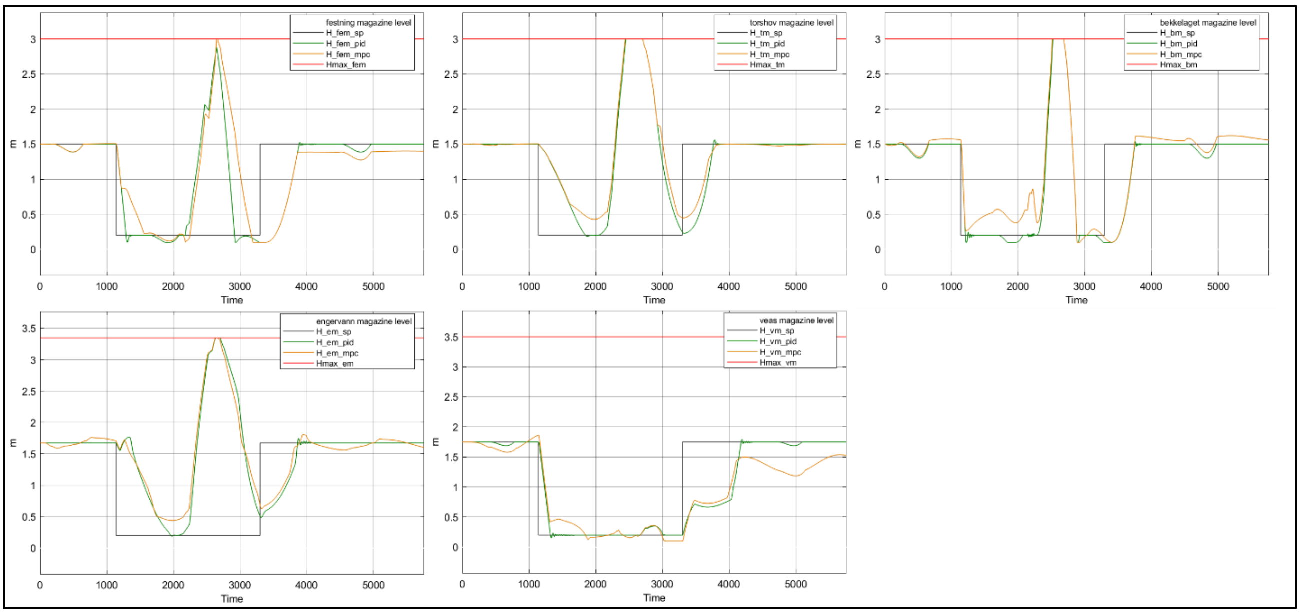

Figure 6: *Rain event 4, controlled variables (levels) in Frognerparken magazine, Torshov magazine, Lysaker magazine, Bekkelaget magazine and Veas magazine using the feedforward strategy combined with PI-controllers (magenta), MPC algorithms (yellow). The setpoint is indicated with black line and the high-limit with red line. If the high level is exceeded, wastewater flows over to natural waterways.*