

The Potential of Real Time Control to reduce Combined Sewer Overflow

K. Broks, A. Geenen and F. Nelen

Dept. of Sanitary Eng. & Water Mgm., TU Delft, The Netherlands

P. Jacobsen

Dept. of Environmental Eng., TU Denmark

The potential of Real Time Control (RTC) to reduce the overflow volume from a combined sewer system has been investigated for a catchment in Copenhagen, named Strandvaenget. The results have been compared with the alternative of increasing the storage volume of the system. The RTC strategy has been derived using a mathematical optimization and a rule based method. As the only objective is to reduce the Combined Sewer Overflow (CSO), the developed rule based control algorithm can achieve almost the same results as the optimization method.

From the results of time series calculations, it can be concluded that the introduction of RTC appears very promising when the mean yearly CSO volume has to be reduced. In this research, the potential of RTC is investigated for an increasing amount of storage volume and for an increasing demand for reduction of CSO volume.

Introduction

In Denmark, about 50% of all sewer systems are combined sewer systems. Since Combined Sewer Overflow (CSO) may seriously impair the water quality of the receiving water body, they need to be reduced. This can be accomplished in several ways. Two plausible solutions are discussed and compared in this article.

The first solution is to enlarge the storage capacity of the system (*e.g.*, by means of detention basins). In this way more sewage can be kept within the system. Se-

condly, with the introduction of Real Time Control (RTC) a more effective usage of the existing hydraulic capacities can be obtained. By controlling the system, profit can be taken from three aspects:

- 1) the inflow is distributed in time and space,
- 2) the system capacities are distributed in time and space,
- 3) the effects of the system output are variable in time and space.

The latter is not considered in this study. Nor has areal rainfall distribution been taken into account.

Combinations of both increasing the storage capacity and using RTC are investigated as well. The possible reduction of CSO volume compared to the present situation (expressed in reduction rates) is quantified for an increasing amount of storage volume until a reduction rate of almost 100% is reached. The catchment Strandvænget (North-Copenhagen) is subject of the case study.

Control of Urban Drainage Systems

RTC is a control concept in which the set points of the flow regulator at the regulator site depend on the currently measured system state and possibly predicted sewer inflow. The desired system behaviour is translated into an operation strategy which describes the set points at the controllers in time. The possible control concepts can generally be divided into three groups:

- 1) local control, the controlled variable is measured at the regulator site,
- 2) regional control, the controlled variable is measured at more than one site,
- 3) global control, the control actions of every regulator depend on the whole system state.

The operational problem of finding the best set points can in principle be solved by:

- 1) heuristic methods, the problem is solved by gained experience,
- 2) rule based methods, the problem is solved by comparison of several system variables, often an IF ... THEN ... ELSE ... structure is used,
- 3) mathematical optimization, in which the desired system behaviour is translated into an objective function which is minimized, subject to a set of constraints which describe the system.

For a comprehensive description of RTC-concepts see (IAWPRC Taskgroup on RTC of UDS 1989).

In this case the operation strategy is found by mathematical optimization of a cost function. Mathematical optimization is the most sophisticated method. Due to its flexibility it is the most suited method for a system analysis aimed at an assessment of the potential of RTC. This approach is implemented in the LOCUS package. LO-

CUS is an acronym for Local *versus* Optimized Control of Urban drainage Systems and has been developed at the Technical University of Delft (Nelen 1992). It is based on the minimization of a non-linear objective function, subject to a set of linear constraints (lumped storage approach), using “non-linear programming” (Schilling *et al.* 1987; Petersen 1987 and Nelen 1992). The model can be used to simulate the present uncontrolled situation as well, using the same schematization. By comparing the results, the potential of RTC is indicated (see also Mooijman *et al.* 1992).

In this study the objective function is formulated such that the use of storage is optimized in order to reduce the CSO volume. To obtain this, a relatively high weighing factor is given to the use of storage and a very high weighing factor is given to the CSO volume. Minimization of the cost function, which is based on the actual and predicted system state in all nodes, will result in a control strategy by which the overflow volume is kept to a minimum.

In this paper it is shown that efficient use of the storage capacity can also be achieved by a relatively simple rule based control strategy. This strategy is based on the following principle.

As soon as an overflow occurs, all available storage capacity should be used to its maximum. In a rule based strategy, this desired behaviour can be realized by keeping the use of storage at the various sites at a relatively equal level. As this approach is rather straightforward, it should be possible to obtain the same results with a rule based scenario.

Rule Based Control

In case of a combined sewer system the hydraulic load consists of dry weather flow and storm weather flow. As the inflow during a rain event is strongly related to the size of the connected area, the capacities will be expressed in specific capacities. The specific storage and discharge are defined as respectively the storage volume (including detention basin volume) and the discharge capacity of a sub-catchment, divided by the connected impervious area. The specific free storage (SFS) is the available storage capacity in a sub-system, related to the size of the impervious area connected to that sub-system (expressed in mm rain).

The decision model is based on a comparison between the system state in two serial basins. The objective of the control algorithm is to reduce the CSO volume by means of:

- 1) using the discharge of the whole catchment at its maximum (the treatment plant is assumed to be able to receive this maximum load),
- 2) striving after equal preparation for a future sewer inflow for all sub-catchments. Ideally, no overflow should occur in any sub-catchment before all are completely filled, if physically possible, as the strategy aims at balancing the available free storage in the system.

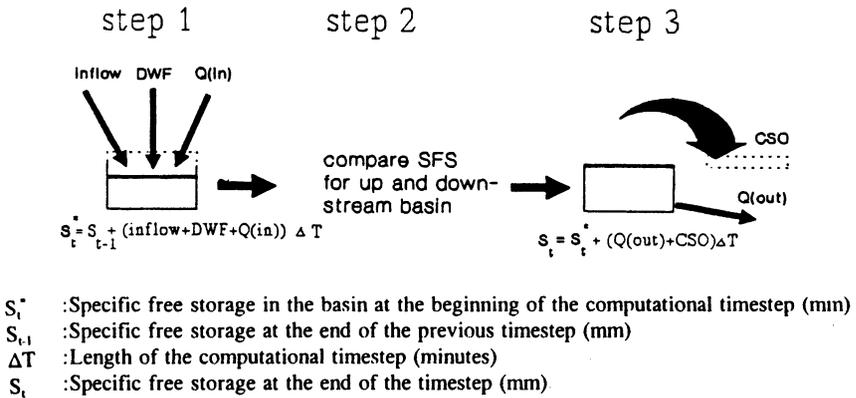


Fig. 1. Waterbalance lumped storage model, based on an explicit scheme.

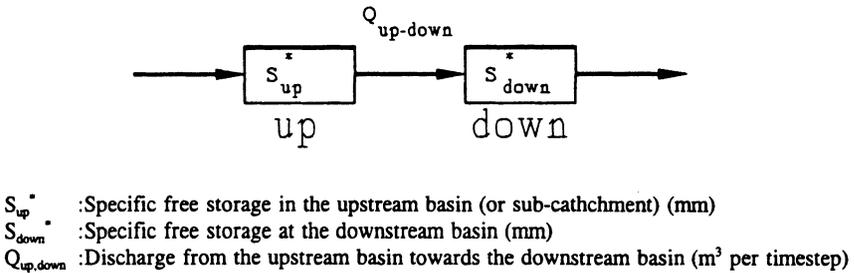


Fig. 2. Parameters in the control algorithm at step 2.

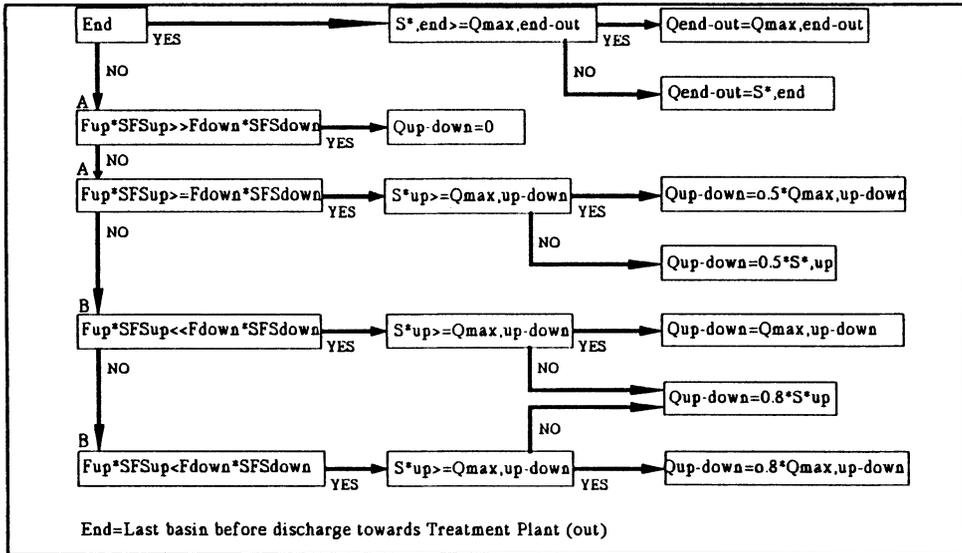
When comparing the SFS of the up- and downstream basin, the combinatory effects of the specific free storage and the specific discharge capacity must be taken into consideration. Therefore a factor is introduced for each basin. The main purpose of this factor is to induce discharge towards a downstream basin with a smaller SFS compared to the upstream basin, while the situation in this downstream basin is not critical. As soon as the SFS in the downstream basin becomes small, the discharge will be reduced. For every catchment another set of factors will be found. The factors have no strict physical meaning.

The calculation of the discharge comprises three steps (Fig. 1). The three steps will be executed for each basin and for each timestep within the rain event.

At step 2 the system state of the up- and downstream sub-catchments are compared (Fig. 2).

If the upstream sub-catchment is “better” prepared for a future sewer inflow, the discharge towards the downstream section should be small or zero. The same holds true the other way round. This concept is described by the following flow algorithm (Fig. 3).

Real Time Control of Combined Sewer Overflow



- End :Last basin before discharge towards Treatment Plant
- S*,end :Specific free storage at the "End-basin" (mm)
- Qmax,end-out :Maximum discharge form End-basin towards the Treatment Plant (m³ per timestep)
- Qend-out :Discharge form the End-basin towards the Treatment Plant (m³ per timestep)
- Fup :Factor for calculation of the specific free storage of the upstream basin
- SFSup :Specific free storage of the upstream basin (mm)
- Fdown :Factor for calculation of the specific free storage of the downstream basin
- SFSdown :Specific free storage of the downstream basin (mm)
- Qup-down :Discharge from the upstream towards the downstream basin (m³ per timestep)
- Qmax,up-down :Maximum discharge from the upstream towards the downstream basin (m³ per timestep)
- S*up :Specific free storage of the upstream basin (mm)

Fig. 3. The control algorithm.

In the A-category the upstream reservoir is better prepared on a future disturbance.

Whether a comparison is regarded as the '>>' or '>' category depends on the size of the specific discharge. In the B-category the downstream reservoir is better prepared on a future disturbance to come. Whether a comparison must be regarded as the '<<' or '<' category also depends on the size of the specific discharge. The algorithm is described in detail in (Broks and Geenen 1993).

Comparison between the Optimized and Rule Based Control Algorithms

Both the rule based control and the optimized control algorithm aim at reduction of CSO volume and derive their control strategy based on the actual system state.

The two algorithms differ basically on the following aspects:

- the optimized control algorithm derives the control strategy using volumes (m^3) whereas the rule based algorithm uses depths (mm);
- the optimized control algorithm bases its control decisions on the whole systems state, whereas the rule based algorithm bases its decisions on every two neighbouring sub-catchments;
- in the optimized control algorithm the weighing factors for discharge, storage and overflow have to be defined, whereas in the rule based algorithm the discharge factors has to be defined. The weighing factors represent a direct translation of the objectives, while the purpose of the discharge factors are mainly to induce the discharge towards downstream basins while the SFS in the system is still large.

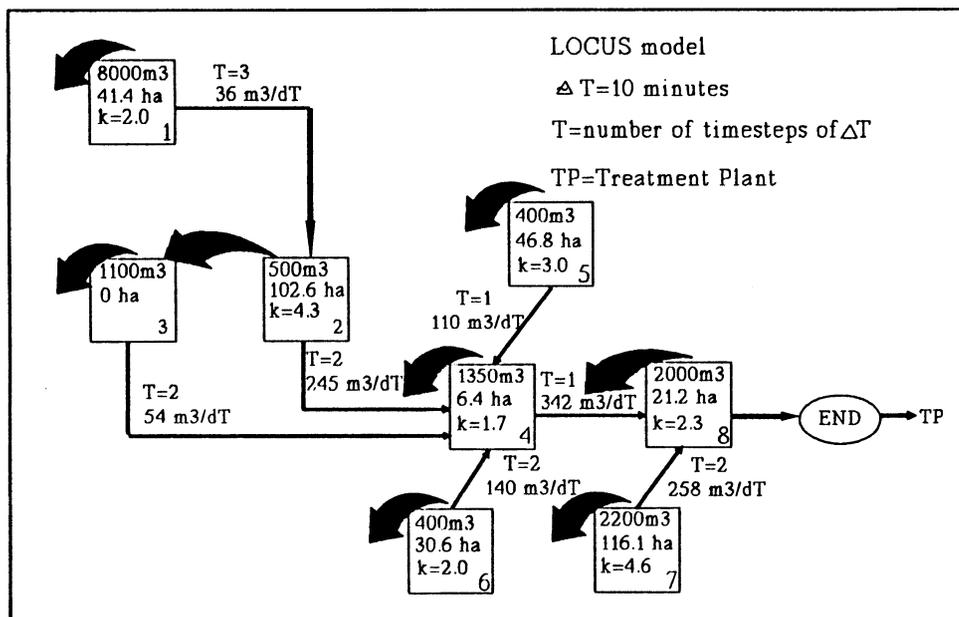
Although the two algorithms differ strongly, it can be shown that in case their main objective is to reduce the CSO, the results of both control strategies are almost the same.

Case Study: Catchment Strandvaenget, Copenhagen

The catchment is part of the urban area of North-Copenhagen, with about 91,000 inhabitants. The total connected impervious area amounts to 365 hectare. The sewer system is combined. The waste water from the catchment is drained towards the treatment plant 'Renseanlaeg Lynetten' in the greater Copenhagen area. The CSO from the sewer system is discharged into the lake 'Utterslev Mose', a former swamp with a large retention time. Accumulation of nutrients and heavy metals caused by CSO have deteriorated the water quality of the lake. Therefore, a reduction of the mean yearly CSO volume is needed. The most effective ways to reduce the CSO volumes, which are discharged into Utterslev Mose, must be investigated. In this case study the potential of RTC (using both control algorithms) for a large range of possibly demanded CSO reduction rates (0-95%) is presented and compared with the potential of the enlargement of the storage capacity.

Schematization

The catchment Strandvaenget has been schematized into a lumped storage model (Fig. 4) to be able to simulate long time series of historical rain events. The storage volume and overflow constructions are concentrated in nodes. Between these nodes relations are defined concerning discharge capacities $Q_{\max,i}$ and flowtimes T_i . In



- First line in square :Storage capacity of the basin (m^3)
- Second line in square :Impervious area (hectare)
- Third line in square :Linear reservoir coefficient
- Right-bottom corner of square :Number of the basin
- ΔT :Length of the computational timestep (minutes)
- First line next to arrow :Time of travel between the basins (expressed in number of timesteps)
- Second line next to arrow :Maximum discharge from the basin (m^3 per timestep)

Fig. 4. Lumped storage model of the catchment Strandvænget.

LOCUS, a fixed relation between discharge and waterlevel, $Q-H$, is used to describe the uncontrolled flow routing. So the discharge from a reservoir only depends on the water level in that basin. Hydrodynamic effects (like backwater) cannot be simulated.

The lumped storage model has been derived from a SAMBA schematization. This SAMBA schematization has been derived from the simulation of 9 rain events with the MOUSE model, using the dynamic wave approach (Jacobsen and Jensen 1990). For a description of the MOUSE and SAMBA model, see MOUSE manual (1992). The LOCUS model results are tuned on the SAMBA results. In this way a reference is created. The rainfall intensities are translated into sewer inflow for each node by means of a linear reservoir model. Each reservoir (node) has its own connected area, $A_{imp,i}$ and reservoir coefficient (k_i).

The system consists of eight basins. Seven basins have connected area, basin 3 is

a detention basin which belongs to basin 2. The sub-catchment data are given in Table 1.

To get a right impression of the mean yearly CSO volume, the Odense time series of 33 years of rain events is used. From a statistical point of view the effects of the areal rainfall distribution are not significantly influencing the mean yearly CSO volume (Mooijman *et al.* 1992).

Rain events with a rain depth exceeding 3 mm are used in the calculation. Rain events are defined so that they contain a maximum dry weather period of 1 hour. These selection criteria are used to reduce the computation time. In this way 1571 rain events are selected.

Table 1 – Modelparameters of the present situation ($\Delta T = 10$ minutes)

basin	$S_{\max,i}$ [m ³]	$Q_{\max,i}$ [m ³ /ΔT]	T_i [ΔT]	$A_{\text{imp},i}$ [ha]	Iniloss [mm]	k_i [ΔT]	DWF [m ³ /ΔT]
1	8000	36	3	41.4	0.6	2	17
2	500	245	2	102.6	0.6	4.3	41
3	1100	54	2	0	0.6	1	0
4	1350	342	1	6.4	0.6	1.7	3
5	400	110	1	46.8	0.6	3	19
6	400	140	2	30.6	0.6	2	12
7	2200	258	2	116.1	0.6	4.6	46
8	2000	600	0	21.2	0.6	2.3	8
Total	15950	–	–	365.1	–	–	146

Scenarios

The aim is to assess the potential of RTC on the whole range of possibly demanded reduction rates of CSO volume. Therefore several scenarios have been simulated with all three control options (uncontrolled, rule based and optimally controlled):

- cal-0, the present situation serves as a reference,
- cal-1, small structural adaptations in reservoir number 3 can yield 4,400 m³ additional storage volume in a cost-effective way,
- cal-2 and further, these are the other reduction scenarios. The system will be further enlarged with additional storage volume at the most effective locations.

The differences between the model results of the various types of control options, simulated with the same hydraulic characteristics and the same hydraulic load, are only due to the different type of control.

Real Time Control of Combined Sewer Overflow

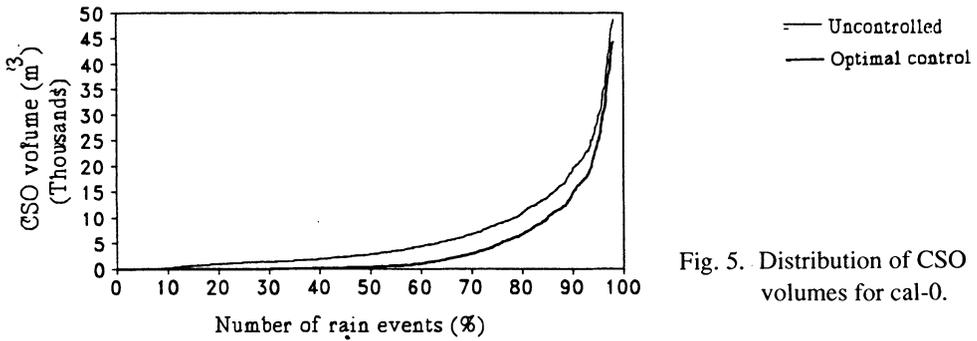


Fig. 5. Distribution of CSO volumes for cal-0.

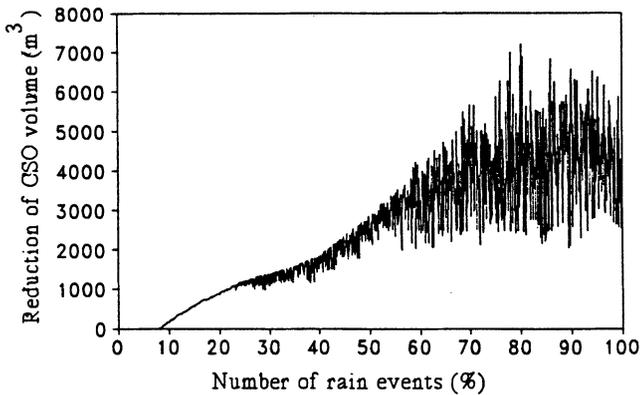


Fig. 6. Reduction of CSO volumes for cal-0.

Results

The optimized control algorithm tries to prevent overflow as much as possible. The specific CSO volumes will therefore tend to become the same for the various nodes in the whole catchment. Both large and small rain events (with respect to CSO volume) show a decrease in CSO volume, when comparing the results of the optimally controlled with the uncontrolled situation.

In Fig. 5 the distribution and reduction of CSO volume is depicted. The CSO volumes are put in ascending order. The enclosed area between the two curves indicates the CSO volume that can be prevented by the introduction of optimal control. Small rain events (with respect to CSO volume in the uncontrolled situation) can be eliminated completely in the controlled simulations. This is possible as long as the rainfall intensity does not exceed the hydraulic capacities for a certain time (van Leeuwen and Breur 1993). Large rain events show a relatively smaller reduction rate.

In Fig. 6 the differences between the uncontrolled and controlled CSO volume are plotted. Here, only the CSO volumes of the uncontrolled situation are put in ascending order, from which the CSO volume with optimal control of the corresponding rain event is subtracted.

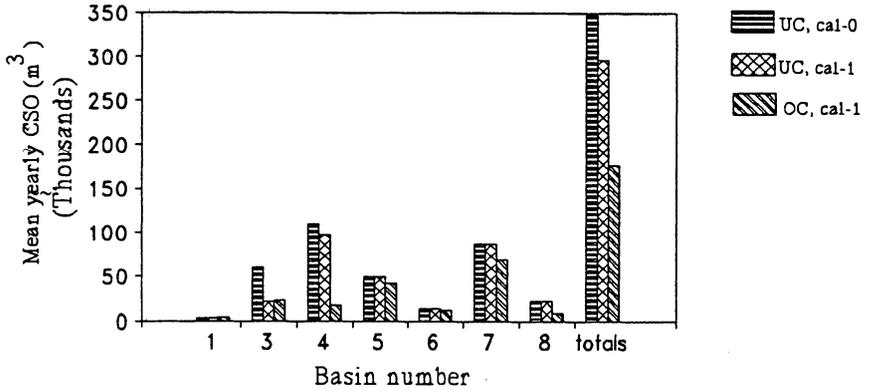


Fig. 7. Mean yearly CSO volumes for cal-1.

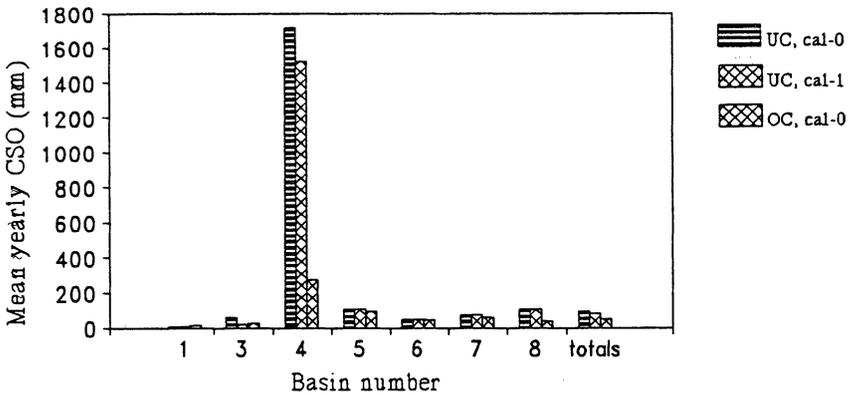


Fig. 8. Mean yearly CSO depth for cal-1.

The differences in the reduction to be obtained by optimal control for large rain events are significant (variations up to a factor 3.5), depending on the characteristics of the individual rain events.

In Figs. 7 and 8 the results of the uncontrolled (“UC”) and the optimally controlled (“OC”) situation for scenario cal-1 (4,400 m³ created in basin 3) are depicted. The CSO volumes and depths are compared with the reference (“UC, cal-0”). In the uncontrolled situation, only a reduction is achieved in basins 3 and 4, as the other basins are not influenced. In the optimized situation positive effects are seen also at other sites. The specific CSO volume (depth) tends to become the same throughout the whole catchment (Fig. 8). The total reduction rates that can be achieved with RTC are 33% in scenario cal-0 and 49% in scenario cal-1. Note that all the reduction rates are given compared to the reference (UC, cal-0).

In the other scenarios the additional storage volume is put at the most effective lo-

Real Time Control of Combined Sewer Overflow

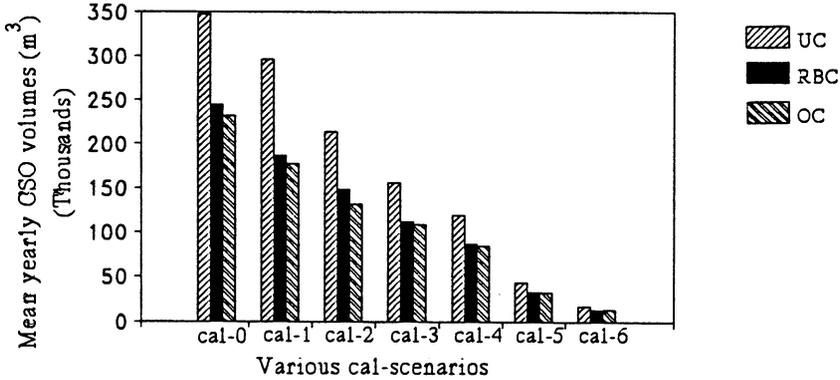


Fig. 9. Mean yearly CSO volumes for 3 types of control.

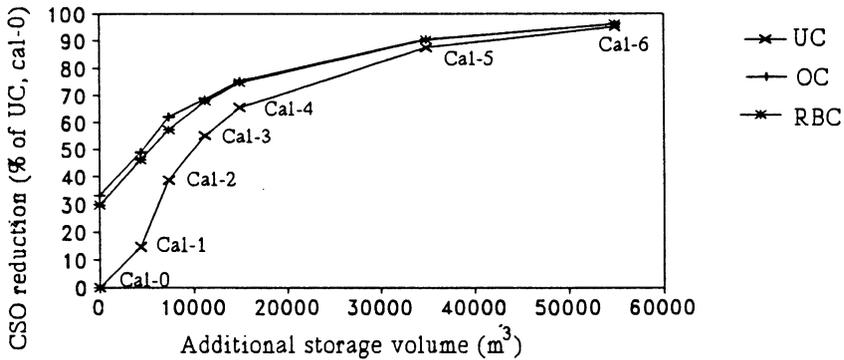


Fig. 10. Reduction curves for 3 types of control.

cation to reduce the CSO volume. The highest overflow frequency pointed the most effective location. In general, the specific capacities of the system will become more homogeneously distributed over the system.

All six scenarios are simulated with no control, rule based and optimal control. The results of the simulations are summarized in Fig. 9.

The differences between the optimal and rule based control results are very small. This was expected because the rule based control concept can realize the same effective usage of the system capacities. Although the algorithms (thus the system evaluation) for the optimal and the rule based control are different, the discharge decisions of both control algorithms are comparable. Large rain events (with respect to CSO volume) show almost the same results for optimal as for rule based control. For the smaller rain events the optimal control algorithm will, on an average, gain a higher reduction rate than the rule based control algorithm. In the scenarios where the specific capacities of the system are more homogeneous, the reduction rate with

rule based control is almost the same as achieved with optimal control (Fig. 9).

The reduction curves (Fig. 10) show the difference in possible reduction of mean yearly CSO volume between on the one hand, enlargement of the storage capacity and on the other hand enlargement of the storage capacity in combination with the introduction of RTC.

The crack in the curves at cal-1 indicates that the additional storage volume has not been placed at the best location with respect to CSO reduction, but at the most cost-effective location.

The RTC simulations always show a higher reduction rate compared to the uncontrolled simulations for the same scenario. As in the last scenarios the CSO volume is more determined by the extreme rain events, the relative difference between the uncontrolled and controlled simulations will be smaller (Fig. 10).

Conclusions

In this study the potential of RTC to reduce the CSO volume is quantified and compared with the enlargement of the storage capacity of the system, without RTC. Without RTC the required extra storage for the same reduction rate as in the controlled situation is considerable (Fig. 10). RTC shows a large potential to reduce CSO due to the large discharge capacities which are available in the system.

As in this study the reduction of CSO is the only objective, the operational problem can mathematically be solved with a rule based method. The algorithm is less complex than an optimization algorithm and is based on a comparison of the system state in two serial sub-catchments. Almost the same reduction rates can be realized as achieved with the optimized control.

To reduce the CSO volumes discharged into the lake Utterslev Mose, it is advised to create 4,400 m³ additional storage volume in detention basin 3. At this location, this is relatively easy to realize. Together with RTC, this results in a reduction rate of CSO volume of about 45%. Without RTC the required extra storage volume for the same reduction rate would be about 9,400 m³. So, in this case study the potential of RTC equals 5,000 m³. When higher reduction rates are demanded, additional storage volume can be implemented or other measures to reduce the CSO volume must be taken into consideration (*e.g.* storm water infiltration).

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Real Time Control of Combined Sewer Overflow

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Address:

Kees Broks,
DHV Environment and Infrastructure,
Postbus 1076,
3800 BB Amersfoort,
The Netherlands

Sander Geenen,
Witteveen & Bos, Consulting Engineers.
The Netherlands

Per Jacobsen,
Department of Environmental Engineering,
Technical University of Denmark,
Building 115,
DK-2800 Lyngby,
Denmark.

Fons Nelen,
Department of Sanitary Engineering & Water Management,
Technical University Delft,
P. O. Box 5048,
2600 GA Delft,
The Netherlands.