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Systematic Design of Distributed Controllers for Sewer Networks

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Abstract: A novel concept for a systematic design procedure of a distributed controller network for global control of a sewer network is proposed. This concept is based on two simple controller types (local throttle controller, supervisory controller) which are connected systematically based on the structure of the sewer network and the available throttle and storage structures. The controllers are based on simple algorithms (nonlinear P-control, simple prediction models) which can be implemented in standard programmable logic controllers (PLCs). Design rules for the controller parameters are available. An appropriate simulation system allowing the design, test and validation of the developed concept which has been set up. The simulation system allows the description of the controllers using a standard PLC programming language (IEC 61131 ST). Finally, an example is presented to demonstrate the ability of the control concept to utilise a high percentage of the theoretically available improvement potential for automatic control. The approach presented is expected to be easily applicable in real cases and to reduce the typical effort required for the application of automatic control to sewer networks by at least one order of magnitude.

INTRODUCTION

In most cases, the structure of sewer systems forms a tree of sewer pipes collecting the wastewater and (in combined systems) also the rain water (see Fig. 1). Branches of smaller pipes are linked to larger collector pipes. To limit the size of collector pipes, overflow structures (CSO - combined sewer overflow) are placed at relevant locations. The overflow structures will, in the case of heavy storm events, direct part of the runoff water directly into receiving water bodies, usually rivers. Finally, all pipes are connected to one final collector pipe transporting the wastewater to a wastewater treatment plant (WWTP). In order to limit the pollution discharges directly into the river through the CSO structures and also to avoid an overload situation of the WWTP, additional storm water storage tanks are utilised. These tanks store part of the stormwater during rain events and will direct the collected water after the event to the treatment plant.

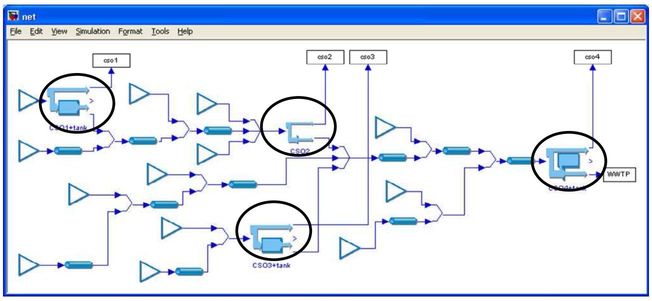


Fig. 1. A typical sewer network structure (Triangles: sub-catchments; pipe elements: flow transport through sewer pipes and channels)

Stormwater tanks are constructed by a combination of a retention tank, a throttle device limiting the onward flow and an overflow structure. The throttle device can be an orifice with a specific cross section area or a controllable valve. Usually, the overflow structure is a weir. In most cases, the whole system is operated without any automatic control (also called "RTC Real Time Control" in urban drainage terminology). The stationary design of the system aims at

- ensuring safe drainage of the area without flooding
- minimising the amount of water and load of pollutants leaving the system towards receiving rivers without any appropriate treatment

It is obvious that the performance of such a system can be improved by automatic control. The performance gain can serve to reduce the necessary investments in stormwater retention tanks and/or to meet stricter regulations or simply to maximise the protection of the environment. Besides this statement, many obstacles exist why control is not applied more often. First of all it is often difficult to gain an economical benefit for improving the ecological performance of a sewer system. In addition, typical approaches for sewer system control require serious effort for development and implementation and may corrupt safe operation of sewer systems.

State of the art for sewer system control can be characterised as follows. Where stormwater storage tanks exist in a system, often local control of the throttle flows of these structures are applied. This local control ensures a level-independent maximum throttle flow and prevents unnecessary utilisation of the storage tank. In rare cases, also a supervisory, global control scheme is applied. Most of the solutions of global control reported can be classified into the following approaches:

- **Rule based control:** The control law is based on rules which are developed and parameterised purely empirical or using mathematical optimisation (Fuchs, Beeneken, 2005, Schütze *et al.*, 2002). This development is based on simulation studies. Rules can be conventional "crisp" logic or sometimes fuzzy rules, sometimes combined with conventional single loop control and model-based predictions of system states.
- **Model based control:** Here a network model for prediction of future behaviour and a mechanism selecting between various options, *e.g.* a mathematical optimisation algorithm, are used to provide the values for the controllable variables (Pleau *et al.*, 2001, Cembrano *et al.*, 2004, Papageorgiou and Messmer, 1985).

Schilling (1989) and Schütze *et al.* (2004) discuss these approaches in more detail. Both approaches have significant demands on manpower for development, test and start-up. The solution promoted in this paper overcomes this obstacle.

APPROACH FOR A GENERALISED CONTROL STRUCTURE

As presented in the introduction, a sewer system forms in most cases a dendritic structure of sewer pipes collecting the wastewater (see Fig.1). Within this tree of collector pipes, CSO and storage structures are placed. These structures are considered here as the potentially controllable devices. If such a structure is utilised as a controlled structure, the application of a unified local controller is assumed. This local controller is used, as usual, to establish a level independent maximum throttle flow (carry-on flow), but in addition

- to define a storage target via a level set-point and
- to formulate a "wish" regarding the maximum throttle effluent, from a local viewpoint.

Fig. 2 shows a simplified scheme of a stormwater storage tank (online configuration) and a local throttle controller.

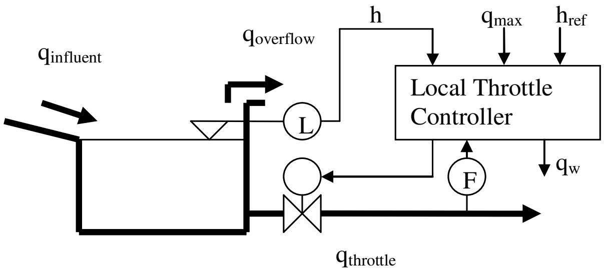


Fig. 2. Local throttle controller

Typically, level and throttle flow measurements are available. Optionally the throttle flow measurement can be omitted and replaced by a level and valve position based calculation of the throttle flow. In the case of only local control, the maximum throttle flow q_{max} is defined as a fixed value (nominal maximum throttle flow), the level reference value h_{ref} is zero, and the signal q_w ("wish" for throttle flow) is of no importance. If the throttle flow reaches the defined maximum value, the valve is utilised to restrict the throttle flow to the maximum value. In dry weather operation, the valve position is fixed at approximately the value representing the maximum throttle flow. This is the conventional behaviour of a local throttle flow controller. The signals q_{max}, h_{ref} and q_w are introduced here for the utilisation of this structure in a global control framework. In this case, the value for the maximum throttle flow and the reference for the level are defined by a supervisory controller, the locally defined "wish" for the throttle flow is directed to the supervisory controller.

In order to maintain a safe local behaviour, it is defined that the value for the maximum throttle flow rate can not be lower than the local default maximum throttle flow. In addition, during local overflow, the valve is controlled in a way that the nominal local maximum throttle flow is established. If the supervisory controller defines a reference value for the level greater than zero, the local control system switches to a level controller, aiming at reaching this reference. For the design of the control algorithm for this purpose, a systematic parameterisation is possible. This is presented in the next section. This approach turns out to be of particular importance where the controllable structure is not just a storage tank with a controllable valve, but a pumping station, where the throttle flow is actively pumped and a rather small storage capacity is available in the pump-sump.

In order to derive the control structure for global sewer network control, the structure of the whole sewer network is simplified to a structure including only the controllable elements (*e.g.* the structures marked in Fig. 1).

Each controllable element has at most one controllable element downstream and might also have controllable elements upstream. In addition to controllable flows from upstream, each element can also receive un-controllable and a-priori unknown inflows from upstream subcatchments. In order to set-up a global control structure, a supervisory controller is placed at each controllable element having controllable elements upstream. This supervisory controller controls the flow from the controllable upstream elements to this element. The local controller of this element (defining the throttle outflow) and the supervisory controller together are now able to control all controllable in and outflows of this element. This allows fairly de-coupled control of this part of the sewer network. The controller network resulting for the example network in Fig. 2 is presented in Fig. 3.

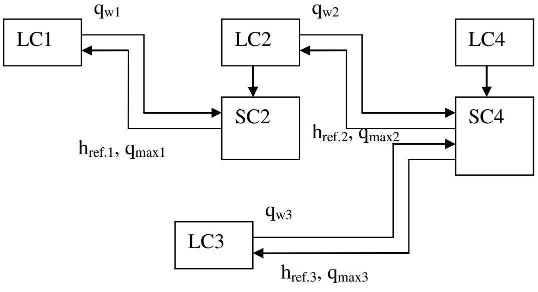


Fig. 3. Controller-Network (LC1..4 local throttle controller, SC2 and SC4 – supervisory controller)

Using this approach, the control system structure arises from the sewer network structure in a natural and straightforward way. The algorithm for the supervisory controller is based on a very simple prediction model for storage volume of the controlled element and two basic objective functions:

- optimum performance is achieved if all tanks are filled synchronously and
- optimum performance is achieved if all flow rate limitations are uniformly utilised.

In order to achieve the first objective, the supervisory controller defines the reference value for the level of all up-stream elements as the current level of this element (with limits and an on/off hysteresis). This ensures that upstream tanks will start to fill whenever a downstream tank starts to fill. For synchronising tanks in the opposite direction, *e.g.* in the case of a filling upstream tank, the local throttle controller of the filling tank is utilised. The local controller of the filling tank formulates a wish for the throttle flow (q_w) which is greater than the nominal maximum throttle flow of this element attempting to empty the related tank and to send more water downstream. This would equalise the level of this upstream tank with the connected downstream tank. But as the downstream part of the sewer network has only limited capacity and also the downstream tank might already be filled, the supervisory controller at the downstream element will check the “wish” of the upstream tank and will limit the wish to a permitted value q_{max} which considers flow and storage limitations. Using these two mechanisms allows the synchronisation of all tanks of the entire system.

The second objective – uniform utilisation of capacities - is implemented as follows: The supervisory controller considers all free flow capacities of the controllable upstream branches and the available storage volume in the downstream storage tank and allocates them to all upstream branches asking for extra capacity (q_w>nominal maximum throttle flow).

Meeting both objectives ensures that all tanks fill uniformly and any overflows occur approximately at the same time and that no flow is limited unnecessarily when free capacities are available. Einfalt and Stölting (2002) have proven that this kind of operation of a sewer network ensures optimum operation in terms of minimum overflow volume. They also describe a simple way to calculate the theoretical optimum for a given storage volume in a sewer network (“Central basin approach”). Such analysis is usually done with a representative long term rain series ($\geq$10 years). It is obvious that the two objectives of the supervisory controller described above will lead to a behaviour similar to the central basin approach. Differences to the theoretical optimum will arise from

- still existing flow rate limitations in the sewer system
- time delays in the coordinated interaction of global controller network and sewer system, mainly from transport delays
- occurrence of control errors (difference between reference and control variable).

All these causes are more or less unavoidable; therefore, it can be expected that the approach presented will utilise – to a very high degree – the practically achievable performance improvement given by automatic control. Calculating this theoretical potential using the central basin approach gives a good indication during master planning about the potential performance of global automatic control.

DESIGN OF LEVEL CONTROLLERS

In practice a wide variety of storage and overflow structures are present. The described approach is applicable for several special cases including:

- overflow structures with no storage (*e.g.* CSO2 in Fig. 1)
- online and offline storage tanks
- in-sewer storage utilisation and
- structures with storage tank but no overflow option.

A frequently available control option is provided by pumping stations. Each pumping station introduces a controllable throttle flow. In many cases, a pumping station may also utilise a significant amount of in-sewer storage. And finally at a pumping station one will frequently find overflow options. From these properties, it is obvious that it might be useful to incorporate a pumping station as a controllable structure in the sense of the presented global sewer network control scheme. For this utilisation, the local controller of the pumping station has to provide the options described in Fig.2 for a local controller. In particular it is necessary to introduce a level reference value and a time-varying value for the maximum throttle (pumped) flow. In conventional pumping station control it is difficult to fulfill these two requirements. Usually, pumps are operated depending on water levels. Threshold values of water levels define when certain pumps within a pumping station are switched on or off. Between the threshold values linear relations describe the frequency-controlled flow rate of individual pumps. A hysteresis is utilised to avoid oscillations. For bigger stations with several pumps, the resulting chart describing the different threshold values becomes easily complicated and dense (small distances between level thresholds). Definition of such threshold water levels is often done by experience and intuition; however, this task is prone to subjective assessment, inflexibility and non-optimality, and possibly leads to unstable behaviour. Determination of such threshold water levels (or of more complex control conditions) often forms a focal part of specifying the control strategy for that pumping station and for control strategies for the entire urban wastewater system.

It is necessary to switch to a more systematic approach for the integration of pumping stations into the proposed global controller network, whilst in other cases it is beneficial.. First of all, the level control law needs to be separated from the task of assigning a set of pumps with specific flow rates to a certain level. It has been suggested by Schütze and Alex (2003) to define first a level controller with a manipulated variable q_{set} which is considered as a reference value for the total flow pumped by the station (See Fig. 4). A subsequent split controller will calculate set points for the individual pumps based on the reference and the recent state of the configuration (hysteresis required).

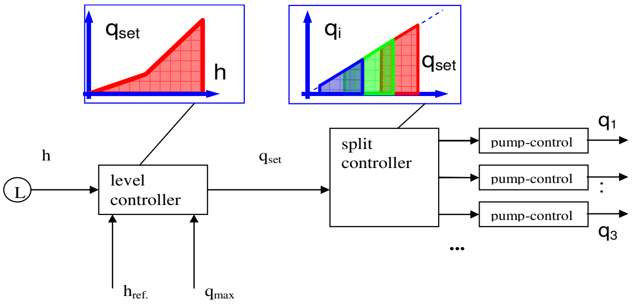


Fig. 4. Suggested pumping station control

The level controller allows now the specification of any appropriate control law (in Fig. 4 a nonlinear P-controller is indicated) where a level reference value can be considered and a maximum flow rate (throttle flow rate) can be defined easily.

A systematic design procedure for such a level controller arises from the following consideration. The stored volume in the pump-sump and in-sewer storage are defined in a simplified manner:

$$\frac{d\,V(t)}{dt} = q_{in}(t) - q_{out}(t) \tag{1}$$

The level h(t) is often a nonlinear function of V(t). This nonlinear function has been found as relevant especially for a relatively narrow pump sump and a widening surface when a channel is filled up. In order to keep the control problem linear, it is assumed that V(t) is calculated from h(t) using the known nonlinear relationship. The pumped flow q_{out} follows the manipulated variable q (flow setpoint) with a significant time delay. Here, a first-order time delay is assumed. Furthermore it is assumed that the measured volume (x) incorporates also time delays arising from the measurement device as well as from additional process dynamics. Details about these smaller time constants are not sensitive, but a general consideration is necessary. From this analysis, the linear model in Fig. 5 is derived.

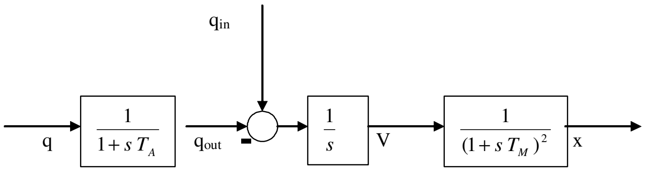


Fig. 5. Simplified model of a pumping station

This model uses the following variables.

Q	manipulated variable, flow set-point
q_{out}	pumped flow
q_{in}	influent from sewer network
V	stored volume
T_A	actuator time constant
T_M	measurement time constant, additional time constant
X	controlled variable, measured volume
W	reference signal (hypothetical)

For a P-controller (with gain K), the reference transfer function follows as

$$F_w(s) = \frac{x(s)}{w(s)} = \frac{K}{K + s(1+sT_A)(1+sT_M)^2} \tag{2}$$

From (2) the roots of the characteristic equation can be calculated. For a dominating time constant T_A (*e.g.* 60s) and two smaller time constants (*e.g.* T_M=30s), the location of the dominating roots depends mainly on the controller gain K and the time constant T_A. For the design rule

$$K = 0.25/T_A \ [m^3/s/m^3 = 1/s] \tag{3}$$

the root location corresponds with a 5% overshoot ratio for a reference step. A tolerable range for K is

$$0.15/T_A < K < 0.4/T_A. \text{ (0-20\% overshoot)} \tag{4}$$

The value $K = 0.8/T_A$ already indicates a maximum value for safe and stable operation. These values can be used to design or analyse a given proportional controller. This is of special importance, since, for the design of a P controller, the gain not only determines the dynamic behaviour but also the maximum flow pumped at the maximum control error. The usage of PI or PID controllers overcomes this limitation, but their usage is not generally recommended, because of the integral characteristics of the plant. The intrinsic steady state errors of a P-controller are of less relevance in this application. However, studies by Schütze and Alex (2003) demonstrate that utilisation of PI or PID provide some additional potential to reduce overflow volume. For this reason, also design rules for PI and PID are derived. For a PI controller

$$F_R(s) = \frac{q(s)}{x(s)} = K\left(1 + \frac{1}{T_N s}\right) \tag{5}$$

the reference transfer function

$$F_w(s) = \frac{x(s)}{w(s)} = \frac{K(1+T_N\, s)}{K\,(1+T_N s) + T_N\, s^2(1+sT_A)(1+sT_M)^2} \tag{6}$$

can be derived. Again the root locations are determined essentially by the controller parameters and the dominating actuator time constant. Because of the integral character of the plant, the integral part of the controller has to be very weak. For $T_N = 10\ T_A$ and $K = 0.25/T_A$ acceptable performance is achieved. Figure 6 presents the root locations for $T_N = 10\ T_A$ and different K values. The roots marked with triangles correspond to $K = 0.25/T_A$.

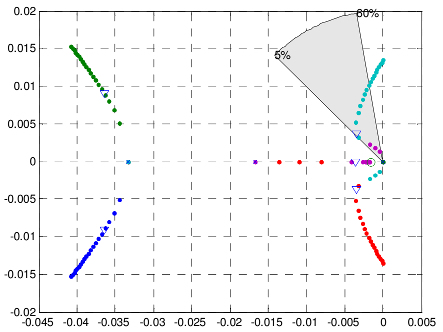


Fig. 6. Root-loci diagram of the characteristic equation (PI)

Analogous considerations can be made for PID control.

The design presented holds primarily for pumping stations but can be also applied to level control of stormwater storage tanks. However, for storage tanks the ratio of maximum volume and maximum throttle flow is typically significantly lower than the ratio of maximum stored volume to maximum pump capacity in pumping stations. For this reason, the selection of a safe and appropriate gain for a P controller is much more relaxed.

DESIGN AND VERIFICATION USING SIMULATION

State-of-the-art for the stationary design of sewer systems including storage tanks and stationary throttle dimensioning is the application of generally accepted simulation models. These models are used to calculate the expected performance for relevant storm events or long term rain series data.

The same methodology is applied for the design and evaluation of the control concepts presented in this paper. Therefore, the simulation system to be used needs to provide appropriate features to describe not only the sewer system but also the planned control concepts. A review of the most widely used simulation systems shows many limitations regarding this aspect. Some systems allow the formulating of control concepts based on simple if-then rules and look-up tables. Others provide tool-specific representations of control concepts *e.g.* based on fuzzy rules. But in general, one will face serious limitations in their ability to represent arbitrary control concepts and none of the existing simulation systems allows the usage of standardised representations used for PLCs (programmable logic controllers).

This situation was one motivation for the development of related libraries of the simulation system SIMBA (ifak Magdeburg), which is based on Matlab®/Simulink™. Using this general simulation platform overcomes the limitations in representing control concepts. In order to additionally support the transfer of developed control concepts into practice, a specific simulation block was developed for Simulink. This block allows the description of a controller using the standardised PLC language IEC 61131 ST (Structured Text). Now the control algorithm from a simulation study can simply be cut and pasted into a real-world PLC program. Fig. 7 shows the implementation of the local throttle controller for a stormwater tank using this approach.

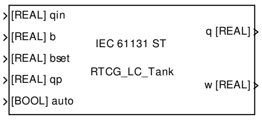
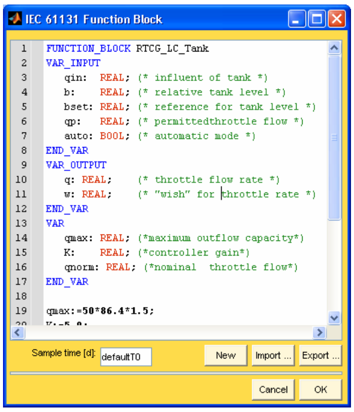


Fig. 7. local throttle controller as Simulink IEC 61131 ST block (left: block symbol: right: dialogue for configuration of the block using ST)



```
FUNCTION_BLOCK RTCG_LC_Tank
VAR_INPUT
   qin:  REAL; (* influent of tank *)
   b:    REAL; (* relative tank level *)
   bset: REAL; (* reference for tank level *)
   qp:   REAL; (* permittedthrottle flow *)
   auto: BOOL; (* automatic mode *)
END_VAR
VAR_OUTPUT
   q: REAL;    (* throttle flow rate *)
   w: REAL;    (* "wish" for throttle rate *)
END_VAR
VAR
   qmax: REAL; (*maximum outflow capacity*)
   K:    REAL; (*controller gain*)
   qnorm: REAL; (*nominal  throttle flow*)
END_VAR

qmax:=50*86.4*1.5;
```

Sample time [d]: defaultT0

EXAMPLE

The presented concept was tested in a number of simulation studies including realistic sewer networks. One simple example is presented in Fig. 8.

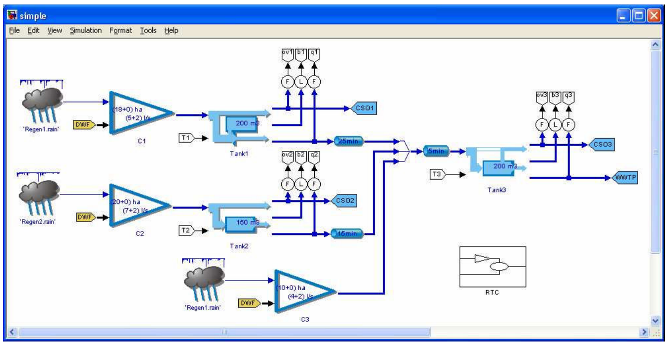


Fig. 8. Example sewer network

This example describes a sewer network with one storage tank placed directly in front of the wastewater treatment plant (tank3) and two upstream tanks (tank1, tank2) in parallel sewer branches. Time series of spatially distributed rainfall are feeding the system. This example network incorporates three different types of stormwater tanks (offline bypass tank, online bypass tank, online pass-through tank) in order to demonstrate the universal applicability of the proposed concept. Following the control concept described, results in the controller network shown in Fig. 9.

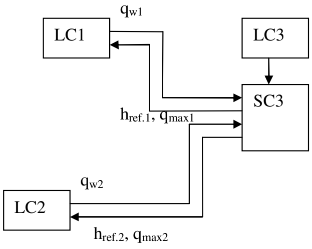


Fig. 9. Controller network

As a reference scenario the system was simulated without global control. The theoretical control optimum was estimated using the central basin approach. Setting up and testing the global control scheme as suggested yields the results shown in Fig. 10.

The presented water levels (top, centre in Fig. 10) illustrate that the simple global control concept presented in this paper achieves a more synchronous usage of the three tanks as compared to the reference scenario. In order to reach this objective, the throttle flow was set dynamically. Overall, this results in a reduced overflow volume (see Table 1).

The result of the proposed control concept is able to approach very closely the theoretical optimum. A detailed analysis of the simulated results shows that only physical limitations regarding the throttle flows prevent this control concept to coming even closer to the theoretical optimum. This result was verified also with more realistic examples and using long-term rainfall time series (30 years).

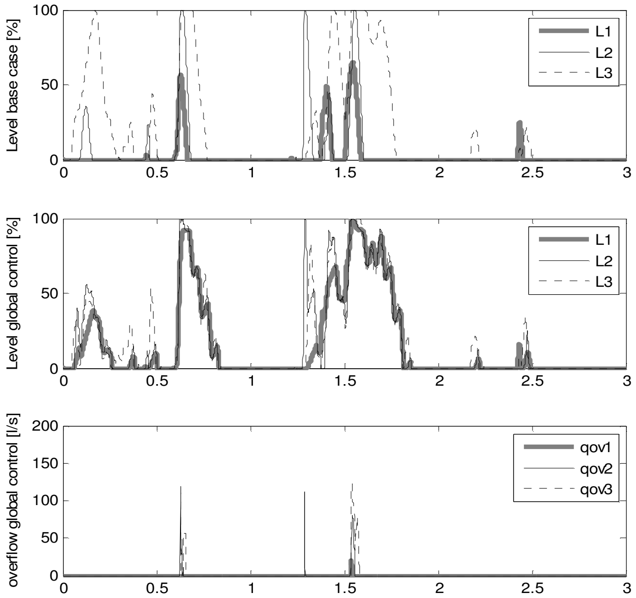


Fig. 10 Performance of the global control scheme of the sewer network; L1..L3 water level in tanks 1..3; qov1..qov3 over flow rates for tank 1..3; top: water level – reference scenario; centre: water level – global control; bottom: overflow – global control

Table 1 Overflow volumes for the simple example

Case	total overflow volume [m^3]
Reference scenario	1040
theoretical optimum	518
global control	540

CONCLUSION

The presented method allows the setting up of global control schemes for sewer networks in a systematic and unified way. The controller network structure results directly from the sewer network structure. Many of the controller parameters are defined by physical parameters of the sewer system. For the remaining parameters simple design rules are proposed.

The effort required is expected to be one order of magnitude less than what is required at present. Despite the simplicity of the modular controller concept, its performance comes close to the minimal achievable CSO volume. This optimum is defined by the theoretical optimum ("central basin approach") and physical capacity restrictions of the sewer network. Therefore, the application of more complex methods (*e.g.* model based control involving optimisation and rainfall prediction) would need very good justifications for their effort.

The proposed concept consists of distributed controllers which easily fall back to safe local operation if communication problems occur. Special emphasis was also put on ensuring that, even for the worst case, the globally controlled system does not behave worse than in the un-controlled case. In many cases the concept can be applied without installation of additional and potentially unsafe equipment. Furthermore, this concept facilitates also integrated control schemes, i.e. joint control of sewer system and wastewater treatment plant (Butler and Schütze, 2005).

The proposed method is limited to sewer systems with a dendritic structure (the majority of systems). For looped networks, empiric adaptations would be necessary. Another limitation arises from the purely volume-based approach. Additional extensions could also include pollution load based control objectives. However, tests indicate that volume-based system optimisation usually also results in good solutions with regard to pollution loads. For practical reasons, control schemes based on very simple measurements (levels and a few flow measurements at throttle devices) are preferable.

Besides the complexity of real world sewer systems the estimation of CSO volumes can by very well simulated using simplified models (including relevant storage structures and CSO structures). Thus even for complex real word applications the proposed method seems to be suitable. Real cases are not expected to be significantly more complex than the presented examples.

The utilisation of a PLC programming language within the simulation environment ensures direct comparability and transferability of the developed controller to a real world PLC.

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