Urban Drainage Systems – Static throttle flows or real time control? A systematic approach to answer this

Systèmes d'assainissement - Régulation statique de débits ou gestion en temps réel ? Réponse par une approche systématique

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RÉSUMÉ

Parmi les options multiples permettant de parvenir à une gestion durable des eaux pluviales, le contrôle en temps réel (CTR) suscite une attention de plus en plus grande. Dans le cadre de la procédure d'évaluation du potentiel du contrôle en temps réel, d'autres mesures devraient être également prises en considération (par exemple le contrôle à la source, les différents réglages statiques des débits maximum dans les dispositifs à goulot). Cet article présente et démontre une méthodologie visant à inclure l'analyse des débits régulés de façon optimisée dans l'analyse du potentiel du contrôle en temps réel. Afin de réduire le lourd temps de calcul d'une application brutale de la procédure d'optimisation, une analyse de la variance est suggérée sous la forme d'une simple analyse de sensibilité comme étape préalable, dont le traitement est encore possible. La méthodologie est démontrée en utilisant comme exemple un projet de réseau d'assainissement à Astlingen, mis au point par le groupe de travail sur le contrôle intégré de la Compagnie des Eaux Allemande (DWA).

ABSTRACT

Among the manifold options to arrive at sustainable stormwater management, real time control (RTC) is receiving increased attention. As part of the procedure to assess the potential of RTC, also alternative measures should be taken into consideration (e.g. source control, different static settings of maximum flows in throttle devices). This paper outlines and demonstrates a methodology to include the analysis of optimised throttle flows in the analysis of RTC potential. In order to reduce the computational burden of a brute-force application of optimisation procedure, an Analysis of Variance is suggested as a simple form of sensitivity analysis as preceding step, which is yet computationally feasible. The methodology is demonstrated using a draft of the Astlingen drainage network set up by the working group on Integrated control of the German Water Association (DWA) as an example.

KEYWORDS

Astlingen, optimisation, real time control, static throttle flows

1 INTRODUCTION

Among the manifold options to arrive at sustainable stormwater management, real time control is receiving increased attention. Real time control is understood as taking active influence in the flow processes in the drainage system by operating, dependent on the current (and possibly past and predicted future states of the systems) control devices, such as movable gates, weirs and pumps (see, for example, Schütze et al. (2004) for a review). Whilst control proves to be beneficial for many drainage systems, it also involves additional efforts (Beeneken *et al.*, 2013). Although the benefits of control, such as adding flexibility and resilience to the system, often outweigh such efforts, a prudent assessment of the drainage system should also consider static measures in an evaluation of potential options.

Often, the static optimisation of maximum permissible throttle flows is advocated as a solution simpler than time-varying permissible throttle flows (hereafter denoted as control). Despite significant earlier work in each of these fields – static throttles (HMULV, 2004), rule-based control, control involving online optimisation (“Model-based control”)(for example, Muschalla, 2009, Joseph et al., 2014, Regneri, 2014), real time control using generalised and easy-to-apply controllers (Alex *et al.*, 2008) – a concise methodology considering and integrating these various schools and approaches is still missing. Thus, the practitioner often gets confused. As a small mosaic stone to structure the procedures, this contribution bridges the gap between consideration of static throttle settings and dynamic variation of throttle settings. This work is related to present work of the working group “Integrated control” of the German Water Association (DWA), which is currently preparing an application manual, illustrating to the practitioner the issues related to setting up a real time control system on an worked example.

2 IMPROVING PERFORMANCE OF A DRAINAGE SYSTEM –BUT HOW?

In order to improve the performance of a drainage system, a multitude of options (including combinations thereof) can be considered. Besides measures such as reducing runoff at source (Source control, Best Management Practices, Low-Impact Design, see Fletcher *et al.*, 2014) or construction of additional storage volume in order to cope better with runoff, also the following represent options of potential interest, and on these the present paper is focussing:

(1) Use of the existing system “as is”, but with different static settings of maximum throttle flows

(2) Use of the existing system in a dynamic way, i.e. by real time control (time-varying settings of maximum flows)

In order to assess the potential of (2), various methods and procedures have been suggested (DWA, 2005, and others). The M180 procedure includes, in its Step 2, an analysis of the potential of alternative approaches. Here, also a systematic analysis should be carried out as to how far one can get with Option (1) for the given drainage system. For this, the following procedure is suggested and demonstrated for the Astlingen system.

3 AN EXAMPLE DRAINAGE SYSTEM - ASTLINGEN

Whilst this example is still under development by the respective working group of DWA, a draft version of this example, as presented and described by Schütze *et al.* (2015) is used here to illustrate the procedure. The system consists of 13 subcatchments, most of which are combined subsystems. Overall, domestic and industrial dry-weather flow amounts to 47.4 l/s, to which 17.5 l/s of infiltration inflow are added, resulting in a total dry weather flow of 64.9 l/s. The catchment area is 620 ha. Total storage volume amounts to 7800 m^3.

As “base” case, it is assumed that the Astlingen drainage system is operated in a static way, i.e. the throttles in the system allow as maximum flows those designated as “nominal flows” in Table 1. These values have been found, for this example, by conventional sewer system design according to the DWA guidelines. Many real-life drainage systems, however, have been modified and extended significantly after its design. Therefore, the static throttle settings obtained long time ago might not be valid anymore. For optimisation of the throttles, a decision has to be made, which throttles are to be considered and which ranges might be permissible. In some cases, for certain throttle structures, a modification of their settings might not be feasible. A brute-force method would now involve to consider all remaining ones in the optimisation process. For these, also their feasible ranges have to be defined. Some guidance results from general considerations (minimum throttle flow larger than peak dry-weather flow; maximum throttle flow not exceeding downstream hydraulic limitations; see also HMULV, 2004). Following such considerations, the minimum and maximum throttle flows for the devices of the Astlingen draft system as shown in Table 1 have been defined.

Table 1: Storage tanks and overflow devices in the [draft] Astlingen system (taken from Schütze *et al.*, 2015)

	type	volume	specific volume	throttle flow [l/s]		
		[m³]	[m³/ha A_{imp}]	minimum	nominal	maximum
	Inflow to WWTP					270,4
tank 1	stormwater overflow tank	1.700	33,1			
tank 2	stormwater overflow tank	870	29,7	15,6	31,3	39,3
tank 3	storage interceptor	3.300	46,2	28,0	129,0	163,2
tank 4	stormwater overflow tank	430	29,3	15,6	29,0	35,8
tank 5	stormwater overflow tank	300	22,0	16,7	35,5	45,1
tank 7	stormwater overflow tank	1.200	23,0	34,2	72,7	92,4
CSO 8	stormwater overflow	0	0,0			94,0
CSO 9	stormwater overflow	0	0,0			510,4
CSO 10	stormwater overflow	0	0,0			151,6
CSO 11	stormwater overflow	0	0,0			158,0
total		7.800	33,5			

To optimise their static settings, would involve the constrained optimisation of a function of five variables (static throttle settings for Tanks 2, 3, 4, 5 and 7; with their respective minimum and maximum values as constraints). Optimisation is understood here as “minimisation of the total overflow volume”, whilst often several concomitant objectives will have to be met (addressed by multi-objective optimisation which has been reported vastly in the literature). Function evaluation consists in carrying out a simulation run with such settings for a predefined input time series of rainfall (which, therefore, should be – in some sense “representative”), Obviously, whilst a range of methods and add-on tools to simulators have been developed (e.g. Schütze, 2007, Henrichs *et al.* 2014 and others), these are not yet integrated with the analyses outlined above under (2).

As function evaluation in this context usually is computationally demanding (unless significant system simplifications are carried out), care has to be taken in the selection and application of the optimisation approach. Instead of “just” applying brute-force optimisation of all throttle devices, it is suggested to do a simple global sensitivity analysis first, in order to establish which throttle exert significant influence. A wide range of sensitivity analysis methods is available (often themselves characterised by huge computational demand); for the present purpose of practical application, a full factorial experiment, varying each of the n parameters (throttle settings) between its minimum and maximum values, results in a feasible compromise between computational demand (2^n function evaluations, which might still be computationally feasible) and resulting system information about importance of parameters (derived by a formal Analysis of Variance). Application of this method is illustrated in the next paragraph.

It is assumed that, in the example drainage system, outlined above, the static throttle settings for Tanks 2, 3, 4, 5, and 7 are subjected to this analysis. Carrying out the 2^5 full factorial experiment and analysing the variance by F tests applying various degrees of freedom (Box and Draper, 1987), gives the results shown in Table 2.

Table 2: Analysis of Variance of influence of static throttle settings

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Location in parameter space:
 Parameter  A: T2   Variation from    15.600000 to    39.300000
 Parameter  B: T3   Variation from    28.900000 to   163.200000
 Parameter  C: T4   Variation from    15.600000 to    35.800000
 Parameter  D: T5   Variation from    16.700000 to    45.100000
 Parameter  E: T7   Variation from    34.200000 to    92.400000

Results of Analysis of Variance:   F value:  Comment:
      Const  94360658278.1952  1029848.2515  significant at the 0.1 % level
     B          5629478732.9212  61439.8939  significant at the 0.1 % level
     A              44037332.2758  480.6216  significant at the 0.1 % level
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E             19204608.4854  209.5983  significant at the 0.1 % level
BE            19204608.4854  209.5983  significant at the 0.1 % level
AB            13706477.3428  149.5919  significant at the 0.1 % level
BC             5069314.7456   55.3263  significant at the 0.1 % level
C              2690142.5849   29.3601  significant at the 0.5 % level
BD             2488710.5209   27.1617  significant at the 0.5 % level
AE              608788.1718    6.6443  significant at the   5 % level
D             296479.4389    3.2358 not significant (not even at the 5 % level)
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These results clearly indicate that the setting of Throttle 5 does not have much influence on the overall overflow volume in this simulation experiment. Therefore, it is discarded from the application of a formal optimisation routine in the next step. Now, the remaining four static maximum throttle flow settings are optimised (for a given rain input time series), i.e. their constant settings within their feasible ranges are optimised, applying the Shuffled Complex Evolution algorithm (Duan *et al.*, 1992) is applied as an example of a derivative-free evolutionary algorithm for constrained optimisation. If it can be ascertained that the objective function is of well-behaved nature without the potential problem of getting stuck in local minima, also a more efficient search should be applied in this step. The optimisation yielded the following optimum settings: T2: 31.6 l/s, T3: 145.4 l/s, T4: 21.3 l/s, T7: 65.1 l/s.

In order to compare the performance of the drainage system with these constant throttle flows against the base case (nominal settings of the flows) and against performance of real time control algorithms, a different rainfall input time series should be used than the one used for optimising the static throttle flows (similar to a sound calibration-validation exercise where also different data should be used for each of these two steps).

Therefore, the drainage system is now simulated for a different historic rainfall time series (of one year duration), this time also employing non-uniform distribution of rainfall. Here, several scenarios are simulated; Simulation of these various scenarios is done using the state-of-the-art simulator Simba# (Ogurek *et al.*, 2015), which allows also the convenient setup and analysis of control systems; its features with regard to systems analysis techniques (including optimisation) are constantly extended. The results of the simulation are summarised in Table 3

Table 3: Simulation results for different control scenarios over one year

Control scenario	Total overflow volume [m^3]
Base case (static throttle flows equal to nominal flows)	908219
Static throttle flows with optimised values as given above	905540
Generalised controller (as in Alex *et al.*, 2008)	877239
Theoretical optimum	835330

These results indicate that, even though for the rain series for which static throttle flows were optimised they yielded good performance (far better than the base case), these do necessarily give low overflow values also for another time series, here being only marginally better than the base case. Therefore, in this example (as in many others), static throttle settings do not increase as much to the flexibility of a system as does real time control. At the same time, for example, a generalised control algorithm, set up with very little effort and without optimisation, leads to improvement of the system.

4 CONCLUSIONS

This paper outlined a small, yet important step to the methodology of assessment of real time control as a potential means to improve a drainage system's performance by comparing the results of optimisation of static (constant) settings of maximum throttle flows against results of real time control. A method, involving an analysis of variance prior to the optimisation procedure, has been proposed and illustrated for the draft version of the Astlingen example system.

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LIST OF REFERENCES

Alex, J., Schütze, M., Ogurek, M., Jumar, U. (2008): Systematic Design of Distributed Controllers for Sewer Networks; IFAC World Congress, Seoul 2008

Beeneken T., Erbe V., Messmer A., Reder C., Rohlfing R., Scheer M., Schütze M., Schumacher B., Weilandt M., Weyand M. (2013). Real time control (RTC) of urban drainage systems - A discussion of the additional efforts compared to conventionally operated systems. Urban Water Journal. 5, 10, 2013, 293-299.

Box, G.E.P.; Draper, N.R. (1987): Empirical model-building and response surfaces; Wiley

Duan Q, Sorooshian S, Gupta V (1992) Effective and efficient global optimisation for conceptual rainfall-runoff models. Water Resources Res. 28,4,1015-1031

DWA (2005). Framework for Planning of Real Time Control of Sewer Networks. Advisory Leaflet DWA-180E 180E, German Association for Water, Wastewater and Waste, DWA, December 2005

Fletcher, T., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.-L., Mikkelsen, P. S., Rivard, G., Uhl, M., Dagenais, D., Viklander, M. (2014): SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage; Urban Water Journal, 2014

Henrichs, M., Leutnant, D., Schleifenbaum, R. (2014) : KALIMOD – Kalibieriung von hydrologischen Prozessmodellen. Programmdokumentation. Fachhochschule Münster.

HMULV (2004) : Leitfaden zur effizienten und sicheren Beurteilung von Schmutzfrachtberechnungen mit dem Modell sMUSI. Anlage 3 : Hinweise zur Optimierung. Hessisches Ministerium für Umwelt, ländlichen Raum und Verbraucherschutz.

Joseph, B., Ocampo-Martínez, C., Cembrano, G. (2014) : Hybrid modeling and receding horizon control of sewer networks. Water Resources Research, 50(11): 8497-8514

Muschalla, D. (2009) Optimisation of Water Resources Systems Using Evolutionary Algorithms, PhD thesis, Technische Universität Darmstadt.

Ogurek M., Alex J., Rieger L., Schraa O., Schütze M. (2015). A novel integrated approach for designing, testing and implementing WRRF process control solutions; WEFTEC 2015

Regneri, M. (2014): Modeling and multi-objective optimal control of integrated wastewater collection and treatment systems in rural areas based on fuzzy decision-making. PhD thesis. Technical University Graz

Schütze, M.; To, T.B.; Jumar, U.; Butler, D. (2002): Multi-objective control of urban wastewater systems. International Federation of Automatic Control 15th IFAC World Congress. Barcelona

Schütze M., Campisano A., Colas H., Schilling W., Vanrolleghem P. (2004). Real time control of urban wastewater systems - where do we stand today? Journal of Hydrology, 299, 335-348.

Schütze (2007): Module zur Systemanalyse (Erweiterungmodule zum Sensitivitäts- und Kalibrierungstool). Internal Report. ifak e. V. Magdeburg

Schütze, M., Györfi, J., Pabst, M., Haas, U. (2015): The Astlingen drainage system – A Benchmark for real time control; 10th International Urban Drainage Modelling Conference (UDM2015); Mont Sainte Anne, Québec, 20. -23.09.2015