CONTROL STRATEGIES BASED ON WATER QUALITY ASPECTS

by Fons Nelen, Delft University of Technology

published in proceedings of:
5th International Conference on Urban Storm Drainage
Osaka, Japan, july 1990

and:
First European Junior Scientist Workshop on
Applications of Operations Research to
Real Time Control of Water Resources Systems
Kastanienbaum, EAWAG rep. series 3, Switzerland, 15-18 March 1990

ABSTRACT: Control strategies based on water quantity parameters only and aiming at maximum use of available storage do not have to be 'optimal'. This paper describes a numerical model to derive optimized control strategies, taking both water quantity and water quality parameters into account and aiming at minimization of pollution loads on receiving waters.

KEY WORDS: linear programming, model, pollution load, real time control, receiving water, treatment efficiency.

1. INTRODUCTION

The general purpose of an urban drainage system (UDS) is to collect, transport and treat sanitary waste water and storm water in order to keep health risks, flooding and pollution on the environment within appropriate safety margins. In this context, UDS stands for the whole complex system of sewer mains, outlets, overflow devices, storage basins, pumping stations, pressure mains and treatment plant(s). An UDS is operated in real time if process data currently monitored in the system is used to operate flow regulators during the actual process. Main objective of real time control (RTC) is to improve the performance of the UDS by means of increasing the flexibility in the operation of the UDS under dynamic loading.

The technology of RTC, including the needed hardware, has become widespread. The key problem when applying RTC is the formulation of the control strategy that determines the time sequence of the setpoints of the flow regulators. Most research that has been carried out in this field show one common feature: the strategies are derived from measurements and/or modelling of water quantity parameters, such as water levels and discharges, and aim at 'optimal' use of available storage and transport facilities in order to minimize flooding and overflows to receiving waters. 'Optimal' performance of the UDS is then interpreted as preventing overflows until all storage facilities are completely filled up. The main objective in designing and operating an UDS is however to minimize the pollution load on the environment in order to maintain a certain water quality of the receiving water. It is evident that to some extent this can be achieved by minimizing the overflow frequency or overflow volume. However, the fact that the pollutograph and the hydrograph may show great differences indicates that water quality parameters should be included in the determination of the control strategy. Furthermore the 'damage' caused by overflows is not only determined by the pollutant load of the discharged sewage but also by the type and purpose of the receiving water. Finally it is stressed that in designing and operating UDS the total system (sewer network + treatment plant) should be taken into account. E.g. a more efficient use of available storage in the system might lead to a longer period of maximum hydraulic loading of the treatment plant which may deteriorate the treatment efficiency, leading to an increase of the pollutant load of the effluent. (Harremoes, 1989).

The model LOCUS (Linear Optimized Control of Urban drainage Systems) is developed as part of a research project at Delft University of Technology in which the potential of integrated RTC systems of the total UDS is being investigated. In this paper emphasis is placed on the rationale behind the model, its structure and its operational basis.

2. THE MODEL

As shown in Figure 1, the model can be divided in three main modules. The needed input consists of a simplified description of the drainage system, inflow and waste water data and a description of the operational tasks of the system, ranked to their priority (cost factors). In the simulation part the objective function is minimized, subject to capacity constraints and dynamic constraints. Furthermore, a simple pollutant transport model is used to indicate the pollutant concentration of the sewage. This parameter, in combination with the sensitivity of the receiving water is used to determine the objective function to be applied. Deviations from the optimum flow rate to the treatment plant are also counted. The main model results are an optimized control strategy, overflows, discharge rates to the treatment plant and an estimation of the pollution load on the environment.

In the following sections the different topics mentioned in Figure 1 will be discussed. The formulation of the control objectives and the needed simplifications highly depend on the used optimization routine, which will therefore be the first topic.

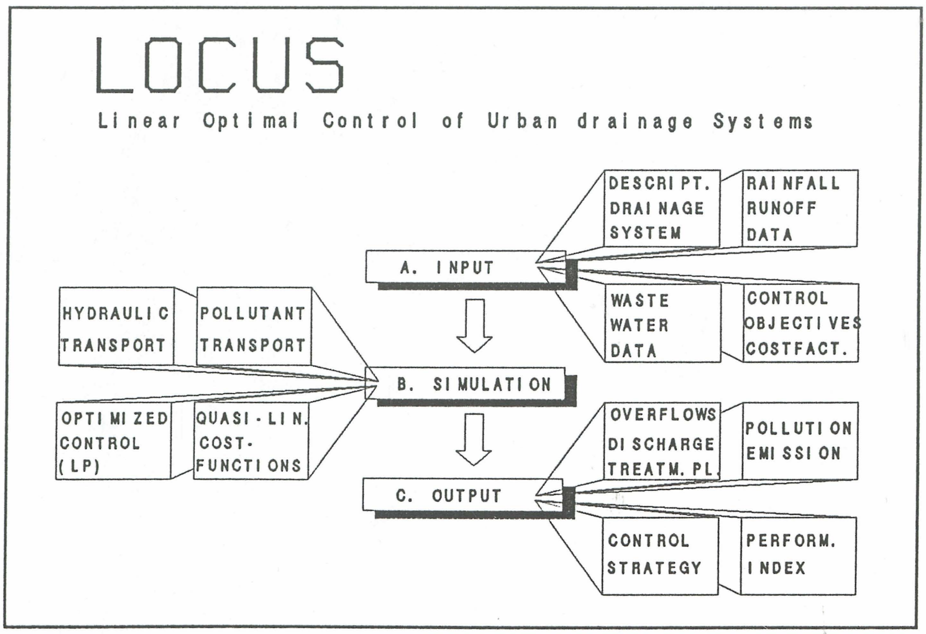

Figure 1. Set-up of LOCUS

3. OPTIMIZATION

There are several ways to derive a control strategy, such as decision matrices, control scenarios based on 'if..then..else' rules, heuristic methods, expert systems and mathematical optimization techniques. The main reason for using an optimization routine is that this approach, if well applied, is most suited to derive a global 'optimal' strategy, which is unique for each event and only depends on the applied objective function. The rationale behind the decisions on the set-points of the flow regulators is clear and consistent. The specification of the operational tasks might give some problems, but that counts for all the mentioned techniques.

Several optimization techniques are available. One of the better known is linear programming (LP) where all decision variables, i.e. state and control variables, and the objective function are linear. Other techniques, such as quadratic programming, dynamic programming (and its derivatives), the maximum principle (two-point-boundary-value-problem), might be more flexible in the formulation of the objective function and/or the dynamic constraints (flow routing), but are less robust and require more computing time and computer storage as LP. The limitation of LP in terms of choice of objective function has (partly) been overcome in LOCUS by applying quasi-linear objective functions, depending on the actual state of the system. This means that the cost factors of each particular state variable may vary in time and place. E.g. the cost factor of an overflow might decrease after a certain overflow duration.

The mathematical formulation of a LP problem is as follows:
Minimize the objective function Z:

$$Z = \sum_{t=1}^{T} \{ c_1x_1(t) + c_2x_2(t) + \ldots + c_nx_n(t) \} \qquad (3.1)$$

with all variables subject to the non-negativity constraint: $x_j \geq 0$ (3.2)
and simultaneously subject to $M = m_1 + m_2 + m_3$ additional constraints,
m_1 of them of the form (upper capacity constraints):

$$a_{i1}x_1 + a_{i2}x_2 + \ldots + a_{in}x_n \leq b_i \quad (b_i \geq 0) \; ; \; i = 1,2,\ldots,m_1 \qquad (3.3)$$

m_2 of them of the form (lower capacity constraints):

$$a_{j1}x_1 + a_{j2}x_2 + \ldots + a_{jn}x_n \geq b_j \geq 0 \; ; \; j = m_1{+}1,\ldots,m_1{+}m_2 \qquad (3.4)$$

and m_3 of them of the form (dynamic constraints):

$$a_{k1}x_1 + a_{k2}x_2 + \ldots + a_{kn}x_n = b_k \geq 0 \; ; \; k = m_1{+}m_2{+}1,\ldots,m_1{+}m_2{+}m_3 \qquad (3.5)$$

In this case, the parameters can be explained as follows:

- T : the time horizon for which inflows can be specified (= m_3)
- n : the number of state variables
- x_n : state variable, e.g. overflow, volume in reservoir, discharge
- c_n : cost factor of the particular state variable
- a_{mn} : constant
- b_i : upper capacity constraints (e.g. maximum storage, maximum flow)
- b_j : lower capacity constraints (in this case 0)
- b_k : dynamic constraints (inflow data)

The input of the model is handled by specifying:

1. the coefficients c_n of the objective function Z (3.1)
2. the upper bound on the variables as defined by the vector b_i (3.3)
3. the inflow data b_k (3.5) for each 'storage unit' of the system (different inflow hydrograhps can be applied in order to include the effects of temporal and spatial distribution of rainfall)
4. the coefficients a_{kn} (3.5), describing the flow routing.

Equation 3.2 is a matter of convention. The model reads the input files, solves the optimization problem, saves the results and modifies the LP problem for the next time step. The search pattern for the optimal solution is based on the revised Simplex Method.

4. HYDRAULIC TRANSPORT

The dynamic constraints of the LP problem form the flow routing model. To specify the dynamic constraints, equation 3.5 should be written T times for each reservoir, in which T is the time horizon for which inflows can be specified (the influence of different forecast horizons on the control strategy can be investigated by varying T). As the name, Linear Programming, indicates the equations have to be linear. The use of a fully dynamic flow routing model, based on the non-linear de St.Venant equations, is therefore not feasible in LP. Some simplifications have to be made. The normal procedure is to simplify the drainage system as a number of storage units with a certain discharge capacity. Under the assumptions of no backwatering, constant flow velocities and ideal performance of the flow regulators, the dynamic constraints can be determined by simple time-shift routing of water volumes:

$$\text{Storage}(t+1) = \text{Storage}(t) + \text{Inflow}(t) - \text{Outflow}(t). \tag{4.1}$$

A verification of the LP results can be made by using a fully dynamic flow routing model with the computed control strategy. LOCUS has until now only been applied for artificial catchments but a similar approach has been used in an investigation for the Bremen catchment in West-Germany. The results of this investigation are encouraging in the sense, that the differences between the results obtained by the hydrodynamic model (EXTRAN-IFW) and the LP program are quite small, which indicates that simple flow routing might perform well for flat systems. (Petersen, 1987).

5. POLLUTANT TRANSPORT

RTC of UDS based on the actual pollutograph seems at present not to be possible as reliable on-line measuring equipment for water quality parameters like e.g. BOD, N and P do not yet exist or need very frequent calibration (Schilling, 1987). Also the simulation of pollutant transport based on a deterministic description of the occurring processes has been less of a success until now. However for this investigation on the sensitivity of control strategies on variations of pollutant concentrations, a simple approach can be applied.

The present version of LOCUS includes a simple pollution transport model, which consists of mixing of contributions of three sources: the inflow of upstream storage units (Q_i) with concentration C_{i1}, a dry weather flow (DWF) with concentration C_{i2} and the sewer inflow (INF) with concentration C_{i3}.

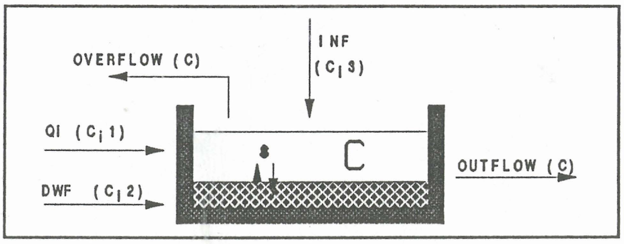

Figure 2. The pollution model

The most simple approach is to assume ideal mixing. However, results of the NWRW study (Hove, 1987) indicate that deposits in sewers form an important source of CSO pollution, due to the low gradient and large dimensions of Dutch systems. If possible, the model should therefore be extended by including the process of sedimentation and resuspension of deposits. In the NWRW investigation it is shown that the average pollutant concentration can be indicated on basis of the inflow intensity. A fairly good correlation was found between the average pollutant concentration and the inflow intensity during periods of 15-30 minutes. At present, the possibility is being investigated to extend the mixing model with a sink term (S), which specifies the removal or growth of matter by sedimentation and resuspension. E.g. S could be assumed to be a function of the inflow intensity and a critical intensity, which determines the initiation of sediment transport. The results of this investigation are too preliminary to set a value for S, which is therefore for the time being set to 0 (meaning ideal mixing).

The pollutant concentration C is not a state variable in the LP problem. (This would require non-linear optimization). This parameter is used in the determination of the objective function. This means that the cost factors of overflows vary in time, depending on the pollutant concentration of the discharged sewage, the duration of the overflow and the sensitivity of the receiving water.

6. TREATMENT EFFICIENCY

In general the introduction of RTC of the UDS means a better utilization of the storage capacity in the system and more water is lead through the treatment plant. This can result in a decrease of effluent quality since the hydraulic load will be higher for a longer period. It is obvious that for RTC of the integrated UDS this phenomenon should be taken into account.

Theoretically it is desirable to control the influent to each part of the plant as all units have their design limitations. To model the total output of pollutants from a treatment plant during storm conditions requires complex models for the main unit operations, such as primary settling, the activated sludge process and the final clarifier (Schilling, 1987). The approach in LOCUS is to concentrate on the discharge from the sewer system to the treatment plant, being the most urgent thing to control. It is assumed that most unit operations of low-loaded activated sludge plants are not much affected by an increase of the hydraulic load as long as the hydraulic design limits are not exceeded. Only under extreme conditions, such as long periods with peak hydraulic loads, a decrease of the effluent quality can not be avoided, due to loss of sludge from the system. In the present version of the treatment module the following parameters have to be specified: the undisturbed treatment (or removal) efficiency, the period of time with maximum hydraulic load after which sludge overflow starts to occur (T_{ti}), the disturbed treatment efficiency and the period of time after the cease of the hydraulic maximum load needed for the plant to recover (T_{tr}). In case of maximum load the efficiency remains constant until T_{ti}. If the duration of maximum load (T_{td}) is longer then the efficiency will decrease. After the cease of the maximum load it takes a period T_{tr} to reach the initial efficiency. The possibility that the period between two consecutive storms is shorter than T_{tr} is taken into account. The pollutant load of the effluent is, as the pollutant concentration of the sewage, not a state variable in the optimization problem, but used in the determination of the objective function.

7. QUASI-LINEAR OBJECTIVE FUNCTIONS

The LP program requires a specification of the operational tasks of the UDS and the 'costs' of not performing these tasks (the cost factors). A major limitation of LP is the fact that only linear objective functions can be applied. In LOCUS this problem is handled by using 'state-dependent' cost factors of each state variable. Each time step, a new optimization problem is formulated as the dynamic constraints (the inflow) vary with every time step. Furthermore it is checked whether new objectives (cost functions) have to be applied. The basic idea behind this, is the fact that the 'damage' on receiving waters, caused by overflows, storm water discharges and treatment plant effluent, show temporal and spatial variations.

Figures 3 and 4 show how the cost factors are determined. The initial cost factor of the overflow (C_{oi}) depends on the discharge point and the type and sensitivity of the receiving water (e.g. stagnant or flowing). The period T_{oi} depends on the pollutant load of the overflow. After a certain load the cost factor will be reduced to C_{or}. After the cease of the overflow it takes a period T_{or} (order: day) for the receiving water to recover. In this period the cost factor will climb to its initial level. The cost factor of the discharge to the treatment plant remains constant until loss of sludge of the system occurs, due to a long period of maximum hydraulic loading (T_{ti}). If the system is disturbed the cost factor will be increased to C_{td} as long as the hydraulic load of the treatment plant is at its maximum (T_{td}). After the cease of the maximum load it takes a period T_{tr} (order: week) for the treatment plant to recover and to reach the initial cost factor.

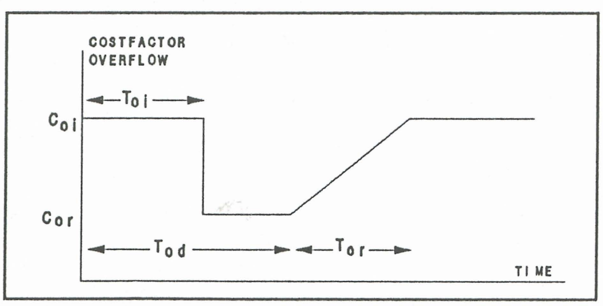

Fig 3. Cost factor of overflow

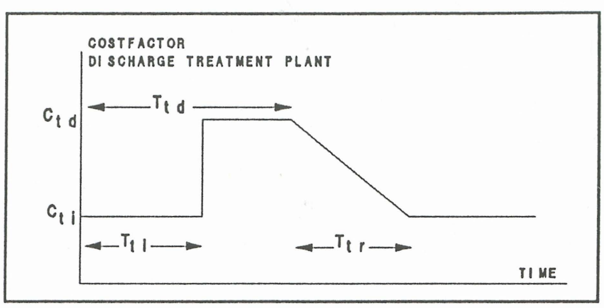

Fig 4. Cost factor of discharge to treatment plant

The objectives are generally difficult to quantify in terms of actual costs. E.g. it is impossible to specify the costs of x m^3 overflow or y mg/l BOD. Another problem is that conflicting objectives have to be included (e.g. minimization of overflows may lead to a higher risk of flooding). The objective function is formulated by giving the different objectives a priority by means of the relative height of the cost factors. It is obvious that a comprehensive sensitivity analysis is required, in order to verify how the objective function influences the optimized control strategy.

8. DISCUSSION AND FUTURE RESEARCH

It has come into focus that the sewer system and the treatment plant have to be designed and operated as one integrated system. The main criterium is to be found in the pollution load on the environment. LOCUS is a tool that can be used to derive optimized control strategies and to investigate the potential of RTC of the total system. Although some computational time is needed, the model allows for long-term simulation to investigate the statistical properties of the pollution emission of the system under 'optimal' control.

At present LOCUS is tested for artificial catchments to investigate the sensitivity of the model results to the height of the cost factors and the variations of the objective functions as shown in Figures 3 and 4. It will be determined till what extend detailed modelling of the underlying processes and/or more sophisticated cost functions will be necessary. Furthermore a sensitivity analysis will be performed on rainfall distribution, forecast horizon and forecast errors. Some of the results will be presented at the conference.

In 1990 the model will be tested for 3 catchments, which are equipped with a supervisory control system. After calibration, LOCUS will amongst others be used as a decision model. By making off-line simulations the operator will be provided with a suggestion for a control strategy.

ACKNOWLEDGEMENTS

The author acknowledge the support of DBW/RIZA (the institute for inland water management and waste water treatment of the ministry of transport and public works), STORA (the Dutch foundation for applied waste water research) and DHV Consulting Engineers BV.

REFERENCES

Harremoes, P, Hansen, O.B., Sund, C., (1989), Rain run-off from sewer systems & treatment plants, proceedings ASCE-conference in Davos, Switzerland.

Hove, D ten, Wensveen, L.D.M., (1987), Invloed overstort-vuiluitworp uit rioolstelsels (Effects of pollution emission from sewer systems; in Dutch NWRW theme 5.

Petersen, S.O., (1987), Real Time Control of Urban Drainage Systems, MSc thesis, TU of Denmark

Schilling, W, e.a, (1987), Real Time Control of Urban Drainage Systems - The State of the Art.