A MODEL TO ASSESS THE PERFORMANCE OF CONTROLLED URBAN DRAINAGE SYSTEMS

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ABSTRACT

The LOCUS modelling package, which has been designed to assess the performance of an urban drainage system that is controlled in real time is presented. Besides the simulation of 'optimal' controlled systems, LOCUS offers the possibility to simulate local (or static) controlled systems as well (i.e. the present way of operation of most urban drainage systems). Since an identical system description is used in both cases, the difference between the results is only due to the way the system is operated and hence the effects of real time control can be quantified by comparing the results. The use of the model is illustrated by a simple example, which shows that it is worth investigating the potential of real time control before constructing extra storage in the system. For a small fictitious system with limited storage capacity at the downstream section it is shown that this potential is comparable to increasing the storage capacity by 1.5 mm at this particular section.

KEYWORDS

Mathematical optimization, non-linear programming, real time control, time-series calculations

INTRODUCTION

For the past decade, numerous (model) studies have been carried out to investigate the effects of real time control (RTC) of urban drainage systems. The popularity of the topic is indicated in Table 1, which gives the number of papers directly related to RTC that were presented at the first five International Conferences on Urban Storm Drainage under the heading of Planning and Management. Most studies on RTC deal with a specific catchment for which a special model has been developed. So far, none of these investigations has led to a general simulation model that is tailored for an assessment of the performance of an urban drainage system that is controlled in real time. Such a model may serve two purposes: it can serve as a rational basis
to assess the potential of RTC in designing or rehabilitating an urban drainage system and it can be used in practice as a tool to derive a suitable operation strategy. Here, emphasis is placed on the first aspect.

<table>
<thead>
<tr>
<th>Place</th>
<th>Year</th>
<th>Papers on Planning &amp; Man.</th>
<th>Papers on RTC</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st ICUD</td>
<td>1978</td>
<td>13</td>
<td>-</td>
<td>0 %</td>
</tr>
<tr>
<td>2nd ICUD</td>
<td>1981</td>
<td>13</td>
<td>1</td>
<td>8 %</td>
</tr>
<tr>
<td>3rd ICUD</td>
<td>1984</td>
<td>44</td>
<td>4</td>
<td>9 %</td>
</tr>
<tr>
<td>4th ICUD</td>
<td>1987</td>
<td>38</td>
<td>12</td>
<td>32 %</td>
</tr>
<tr>
<td>5th ICUD</td>
<td>1990</td>
<td>60</td>
<td>30</td>
<td>50 %</td>
</tr>
</tbody>
</table>

It is stressed that the problem of controlling the urban drainage system in the best possible way must be faced from the start of an urban drainage project. At present, the operational aspects are mostly being considered after the system has been designed and implemented. However, to find the most appropriate solution to urban drainage problems the potential of RTC should be considered in the design of the system, as this early phase provides most flexibility in choosing the appropriate type and size of the flow regulators and in implementing changes in the capacities of the various components of the system.

One of the main requirements in developing the model was that optimum systems performance should be guaranteed (given a set of operational objectives) for each particular system and independently of system disturbances. Moreover, the model should allow for time series calculations, which are necessary to gain insight into the statistical properties of the output variables. In assessing the potential of RTC the simulation results of a single event have no value, as the system investigated and the rain event simulated are unique. A model, called LOCUS (which is an acronym of Local vs. Optimal Control of Urban drainage Systems), is presented that incorporates these features. The use of the model is illustrated for a simple fictitious system.

CONTROL OF URBAN DRAINAGE SYSTEMS

Most urban drainage systems (UDS) are statically controlled, meaning that the set points (desired values) of the local controllers are constant in time. The flow regulators (e.g., pumps, valves) function independently and maintain a pre-set flow related only to the water level at the regulator site. This way of control leads, by definition, to an uneven use of the available system capacities because

- the input of the system (dry weather flow, rainfall runoff) is distributed in time and space;
- the available system capacities are as a rule not homogeneously distributed over the system (in other words, some sub-systems have more capacity available compared with other sub-systems); and
- the effects of the system output on the environment are of different temporal and spatial scale.

Therefore, to make optimal use of the system capacities the set points of the flow regulators should be modified in real time, i.e. on the basis of currently measured process data throughout the system. The time sequence of set points of all flow regulators (= the desired systems state as a function of time) is called the operation strategy (Fig. 1). The decision maker can be an operator (possibly supplied with a decision support system), or an automatic control system.
The operational optimization problem is aimed at finding the optimal set points in time. This problem should not be confused with the control problem, which deals with the determination of the required adjustments of the flow regulators in time (e.g., gate settings, pump rates), to achieve minimum deviation from the (known) set points. Both problems are closely related, as in deriving an operation strategy an important constraint is that the strategy must be feasible.

In the literature, both the terms 'operation strategy' and 'control strategy' can be found, often with the same meaning. Although it is in some cases difficult to make a clear distinction between the operation and the control problem (as they may be solved simultaneously, e.g., when designing multi-variable controllers), it is generally useful to get a clear conception of the problem.

The operational optimization problem

In a general sense, to determine an optimal operation strategy means that the 'cost' (incl. 'damage to the environment') must be minimized, given a perturbation of the system (due to sewer inflow), subject to the constraint that the strategy has to be feasible. In case of a combined sewer system, the general aim is to minimize basement flooding and combined sewer overflows (CSO) to receiving waters, while maintaining optimum flow rates to the treatment plant (depending on its current operational state). If a CSO cannot be prevented, it should be directed as much as possible to the least vulnerable receiving water body.

There are several ways to solve this optimization problem. They may be divided into three broad categories: heuristic methods (i.e. on the basis of experience), rule based scenarios (e.g., decision trees) and mathematical optimization techniques. The last implies that the operational objectives are expressed in an objective function $F$, comprising the 'unit cost' functions of the systems state variables, which is minimized subject to a set of constraints, which describe the system. For a systems analysis this approach is preferred, as it provides maximum flexibility and consistency in the decision process. That is not to say, however, that mathematical optimization is the only possible way to derive an 'optimal' strategy. Especially in the case where the operational objective is restricted to a single aim (e.g. to minimize the total overflow volume, without making a distinction between receiving waters), it is possible to define a more simple and very robust control scenario, which leads to optimum system performance. However, for the above mentioned reasons we confine ourselves here to mathematical optimization.

The operational optimization problem of a system of $n$ nodes (storage elements), with each node $i$ having two outgoing flows $Q_i$ and $O_i$ (the number of flows can obviously be extended) can be formulated as

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**Fig. 1. Scheme of a controlled process.**
\[ \text{minimize } F = \sum_{i=1}^{n} \sum_{t=1}^{T} \left[ cv_i^t \cdot V_i(t) + cq_i^t \cdot Q_i(t) + co_i^t \cdot O_i(t) \right] \] (1)

subject to the continuity equations (for \( t = 1, 2, \ldots, T \))

\[ \sum_{i=1}^{n} \left[ V_i(t+1) - V_i(t) + Q_i(t) + O_i(t) \right] - Q_{i,up}(t) - J(t) = 0; \] (2)

and a set of capacity constraints

\[ 0 \leq V_i(t) \leq V_{i,\text{max}}; \quad 0 \leq Q_i(t) \leq Q_{i,\text{max}}; \quad 0 \leq O_i(t) \leq O_{i,\text{max}}; \quad \text{for } i = 1, 2, \ldots, n \]

where \( n \) is the number of nodes; \( T \) is the number of time steps \( t \) for which inflow is specified (control horizon); \( V_i(t) \) is stored volume at node \( i \) at time \( t \) [m\(^3\)]; \( Q_{i,\text{up}}(t) \) is inflow from upstream nodes [m\(^3\)/\( \Delta t \)]; \( Q_i(t) \) is discharge [m\(^3\)/\( \Delta t \)]; \( O_i(t) \) is overflow [m\(^3\)/\( \Delta t \)]; \( J(t) \) is inflow [m\(^3\)/\( \Delta t \)]; \( cv_i \) is the unit cost of \( V_i \); \( cq_i \) is the unit cost of \( Q_i \); \( co_i \) is the unit cost of \( O_i \); the subscripts \( \text{min} \) and \( \text{max} \) denote respectively the lower and upper bound of the variable; the superscript \( t \) denotes that the particular variable may vary in time.

The simplest option is obviously to apply constant unit cost functions. In that case, Eq. 1, 2 and 3 represent a Linear Programming (LP) problem, which can be solved with standard software. For the past few years, several examples of applications of LP to RTC of UDS can be found in literature, e.g., (Petersen, 1987), (Schilling et al., 1987) and several authors in (EA WAG, 1990).

This approach has, however, some major shortcomings, especially when the control horizon \( T \) does not cover the complete inflow hydrograph (which is a realistic assumption). Petersen and Schilling (1987) have demonstrated that in that case the LP model is quite sensitive to inaccurate inflow predictions. Furthermore it appeared to be difficult to determine the best set of unit costs (which was derived by trial-and-error). This set will theoretically vary for every inflow hydrograph, which means that the LP model is not suited to simulate series of rain events. These problems become less important if the complete inflow hydrograph is included in the optimization problem. However, to describe the dynamic constraints (Eq.2) of a system consisting of \( n \) nodes, \( A \) system variables and a time horizon of \( T \) time steps requires a matrix of \([((A\cdot n \cdot T) + n)\cdot(n\cdot T)]\) entries to be solved, which may restrict the method to smaller problems. An efficient algorithm is necessary to keep the computational time within acceptable limits.

Such an efficient model has been developed at the Institute for Operations Research at Zürich, Switzerland, (Neugebauer, 1989), (Neugebauer et al., 1991). This model, called NOUDS (Network Optimization for Urban Drainage Systems) is based on the LP concept as described above and uses an efficient network flow algorithm to solve the problem. On a 'normal' PC, the model allows control horizons in the order of 250 time steps.

Better results are obtained when the operational problem is formulated as a non-linear programming problem, where the objective function to be minimized depends on the current value of the particular systems state variable (Nelen, 1992). For example, to control the use of storage in the various sub-systems (nodes) it is necessary to increase the unit costs of storage as the degree of filling increases:

\[ cv_i^t = \frac{V_i(t)}{V_{i,\text{max}}} \cdot \kappa_i \] (4)

where \( \kappa_i \) is a constant, denoting the maximum unit cost of \( V_i \) (which may differ for every node). Note that substitution of Eq. 4 in Eq. 1 yields a non-linear programming (NLP) problem.
The unit costs of overflows should be determined on the basis of the function and vulnerability of the receiving water. As overflows are to be prevented as much as possible their unit costs \( (co) \) should obviously be given a greater value than the costs of storage \( (cv) \) and transport \( (cq) \). If necessary, the flow to the treatment plant should be modified according to the actual conditions at the plant. On the basis of such considerations it is possible to formulate an objective function which is valid for all operational conditions.

An effective way to solve the NLP problem is to replace it by a succession of LP problems. This means that at each time step of the simulated inflow hydrograph the optimization problem, as described by Eq. 1, 2 & 3, is re-formulated using the results of the preceding time step. Main advantage of this approach is that it allows the use of a powerful network flow algorithm, by which the model is fast enough to simulate time series of events. Besides it provides a possibility of using variable bounds of the systems state variables (Eq. 3), which may be used to improve the flow routing in the model (this is beyond the scope of this paper, but the principle is based on the concept that the flows along the arcs can be calculated explicitly out of the calculated water levels of the preceding time step).

The NLP model has been incorporated in a newly developed modelling package, called LOCUS, which is an acronym of 'Local versus Optimal Control of Urban drainage Systems'. The name denotes that besides optimal controlled systems, local (or static) controlled systems can be simulated as well (i.e. the present way of operation of most UDS). The latter has been included in LOCUS to serve as a reference. As the reference model and the optimization model are based on an identical system description, the difference between the results of both models is due only to the way the system is operated and hence the effects of optimal control can be quantified by comparing these results.

CASE STUDY

We consider a simple fictitious system that is illustrated in Fig. 2. The upstream sections of the system (Nodes 1 & 2) are sized 'properly', according to Dutch standards. The main problems are expected at the downstream section, at Node 3, where the storage capacity is relatively small. The potential of RTC is quantified here in terms of extra storage capacity that would be required in a local controlled system to achieve the same performance as an optimal controlled system.

The systems characteristics are listed in Table 2. All sub-catchments are identical and the rainfall is assumed to be homogeneous. For convenience the DWF is set equal to zero. Note that in this case only the temporal variability of the system input and the inhomogeneity of the system are contemplated. The effects of the spatial distribution of the system input are in this case excluded.

The rainfall data used for the analyses are historic events that were recorded in Lelystad in 1981. The rain data are transformed into inflow by applying an initial loss of 1 mm and a linear reservoir with a reservoir constant of 15 minutes. The time step used in the simulations is 10 minutes. The system is simulated for five different cases. The storage capacity of Node 3 is increased by 1000 m\(^3\) (= 1 mm) for each successive case.

All cases are simulated using three different operation strategies:

- local control, using a fixed stage-discharge relationship:
  \[
  V_i \geq (0.10 \setminus 0.30 \setminus 0.50) V_{i,max} \quad \text{then} \quad Q_i = (0.33 \setminus 0.67 \setminus 1.0) Q_{max};
  \]
- local control, using a fixed stage-discharge relationship:
  \[
  V_i \geq (0.05 \setminus 0.10 \setminus 0.15) V_{i,max} \quad \text{then} \quad Q_i = (0.33 \setminus 0.67 \setminus 1.0) Q_{max};
  \]
- optimal control, using a control horizon of 1 hour (= 6 time steps). The objective function is formulated so that the use of storage is maximized at all three sub-systems.

Assuming the system is controlled by pumps (the usual case in the Netherlands), the first strategy may be
regarded as more realistic than the second one, as the maximum pump capacity normally is not activated at a degree of filling of 15%. Because only major events are simulated, it is obvious that better results are obtained by applying strategy 2, in which the maximum discharge capacity is activated at a very early stage. Therefore, for a fair comparison between the results of local and optimal control, the results of the second strategy should be used, as when optimal control is applied it is also assumed that the full discharge capacity is available from the beginning of the rain event.

![Fig. 2. A simple fictitious system](image)

TABLE 2. The Systems Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Node 1</th>
<th>Node 2</th>
<th>Node 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imperv. Area [ha]</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Storage Cap. [m³]</td>
<td>7000</td>
<td>8000</td>
<td>5000 *</td>
</tr>
<tr>
<td>Storage Cap. [mm]</td>
<td>7</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Dis. Cap. [m³/h]</td>
<td>700</td>
<td>600</td>
<td>2100</td>
</tr>
<tr>
<td>Dis. Cap. [mm/h]</td>
<td>0.7</td>
<td>0.6</td>
<td>0.8</td>
</tr>
</tbody>
</table>

* : the Storage Capacity of Node 3 is enlarged to 6000, 7000, 8000 and 9000 m³ (= 6, 7, 8, 9 mm)

At the starting point of the calculations, i.e. along the Y-axes of the graphs in Fig. 3, the overflow volumes of Nodes 1 and 2, using Strategy 2, are more or less equal to the volumes as determined for the optimal controlled system. As was mentioned above, strategy 2 (discharge as much as possible) is in this case a suitable strategy for Nodes 1 and 2 to minimize overflows. In the local controlled system the overflow volume of Node 3 is much greater than those of Nodes 1 and 2, which is consonant with the system characteristics. In the optimal controlled system, however, the overflow volumes of all 3 nodes are at an equal level, despite the difference in available storage. By applying RTC, we can make use of the temporal variability of the inflow and attune the system capacities to the current loading, by which a significant reduction of the overflow volume of Node 3 can be achieved, without increasing the overflow volumes of Nodes 1 and 2.

Now, let us consider the effects of increasing the storage or discharge capacity at Node 3. This has obviously no effect on the upstream sections of the system when local control is applied. For the optimization model, however, it means that extra capacity is added to the system that can be used to upgrade its performance. As a result, the overflow volumes of Node 1 and 2 can be reduced, although capacity is added only at Node 3.

As can be seen from Fig. 3, the storage capacity of Node 3 has to be augmented by at least 1500 m³ (= 1.5 mm) to reduce the overflow volume of Node 3 to the level that is achieved by applying optimal control.
CONCLUSIONS

Based on the results of this simple, yet illustrative, case study it can be concluded that it is worth investigating the potential of RTC before constructing extra storage in the system. For a small fictitious system with limited storage capacity at the downstream section it is shown that the potential of RTC is comparable with increasing the storage capacity by 1.5 mm at this particular section.

In this case, the main contributing factor to this potential is the temporal distribution of the system input and the distribution of available system capacities. The effects of the spatial distribution of the sewer inflow, which will have a positive effect on the potential of RTC are in this case not taken into account. (It is noted that the latter is less important as compared to the first two factors).

Moreover, even when it has been decided to add some extra capacity to the system, RTC is still required to improve the performance of the entire system. Applying local control means that the systems performance is improved only locally, i.e. at the site where the capacity has been increased.

This paper illustrates the use of LOCUS in analyzing the performance of an UDS that is operated in real time. For a discussion on 'optimized control' and a more detailed description of the model reference is made to (Nelen, 1992), in which several case-studies using the LOCUS model are presented. A discussion is included on topics like the possible gains concerning the required system capacities, the importance of predicting inflows and effects of prediction errors on the operation strategy, possibilities of controlling the system based on pollution parameters, effects of rainfall distribution and the possibilities of reducing the peak flow to the treatment plant.

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REFERENCES


