HYDROLOGICAL RESPONSE TIMES IN LOWLAND URBAN CATCHMENTS CHARACTERISED BY LOOPED DRAINAGE SYSTEMS

by

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ABSTRACT

Hydrological response times are often used to characterise runoff processes. They provide information about temporal resolution of catchments responses, thus of the required measurement resolutions of in-situ sensors as well as spatial sensors like rainfall radars. The objective of this study was to characterise response times for urban catchments in lowland areas equipped with looped, combined sewer systems. Subcatchments size vary between 0.3 and 7.8 ha. The results show that variation in catchment area size can explain only a part of variation in lag times between the subcatchments. Pipe length per subcatchment explains variations in lag times to a similar, low degree. Comparison of lag time values for looped networks and constructed branched versions of the same networks shows that lag time values are influenced by flow between subcatchments in about half of the looped networks, especially during low flow conditions. This means that in looped systems subcatchment area per exit point varies during a storm event and lag time cannot be related to a single catchment characteristic.

Keywords: hydrology, response time, urban drainage

1 INTRODUCTION

Urban drainage systems in lowland areas are typically characterised by low terrain level variations. In these areas, looped networks are widely applied, because they are more robust to blockages. In looped networks flow directions may change during storm events as subcatchments and their exit points are typically interlinked. As a result, hydrological response times that are often used to characterise runoff processes (e.g. Berne at al. 2004) are more difficult to quantify. Hydrological response times are important for prediction and management of peak flows. Moreover, they are indicative of the spatial and temporal resolution required for rainfall data input into hydrological models. This is especially important for urban water systems because of their short response times resulting in high sensitivity to peak rainfall. It has been shown that existing rainfall input from in-situ rain gauges and radars provide insufficient spatial and temporal resolution to meet the relevant scales of urban hydrology (e.g. Berne et al. 2004; Schellart et al., 2012). Application of dual polarisation radar measurements hold a promise for higher resolution information, but high resolution data come at a cost: the accuracy of high resolution rainfall estimates reduces for higher rainfall intensities (e.g. Van de Beek et al., 2010, Leijnse et al., 2010). Given the trade-off between high resolution data and data accuracy, characterisation of hydrological response times is helpful to decide what resolutions are required to properly model rainfall-runoff processes in urban catchments.

The objective of this study was to analyse characteristic response times for urban catchments in lowland areas equipped with looped and combined sewer systems. In previous studies (see Berne et al., 2004), catchment area size was hypothesised to be an important factor to explain catchment response time. In this response times were related to various catchment characteristics. A method was proposed to delineate subcatchments in looped networks in order to be able to define hydrological response times in such systems.

2 HYDROLOGICAL RESPONSE TIMES IN LOWLAND CATCHMENT AREAS

In this study, hydrological response times for a series of urban catchments in the Netherlands were analysed. Response time is defined in this study as the difference between the centre of mass of hyetograph and hydrograph, also referred to as the lag time. Additionally the time to peak of the hyetograph and hydrograph are...
compared. Characteristics of the three catchments that were analysed, covering a total of 17 subcatchments with separate exit points, are summarised in Table 1.

Table 1 – Characteristics of three looped catchments used for hydrological response time analysis

<table>
<thead>
<tr>
<th>Name</th>
<th>Size (m²)</th>
<th>Imperviousness (%)</th>
<th>Total pipe length (m)</th>
<th>Drainage density (m⁻¹)</th>
<th>No. of exit points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nieuwolda</td>
<td>110517</td>
<td>24</td>
<td>8348</td>
<td>0.08</td>
<td>5</td>
</tr>
<tr>
<td>Scheemda North</td>
<td>266523</td>
<td>23</td>
<td>17936</td>
<td>0.07</td>
<td>10</td>
</tr>
<tr>
<td>Scheemda South</td>
<td>178538</td>
<td>26</td>
<td>11382</td>
<td>0.06</td>
<td>2</td>
</tr>
</tbody>
</table>

2.1 Delineation of subcatchments in looped systems

All analysed systems are combined systems, equipped with one or more pumping stations that pump wastewater and a part of stormwater to a wastewater treatment plant. Each system has several combined sewer overflows, the exit points of the systems during heavy rainfall. In order to delineate subcatchments associated with individual combined sewer overflows, continuous rainfall was applied to the hydrodynamic models in order to reach steady state conditions. Subcatchments were delineated based on flow directions for this situation. Then, the systems were cut up into branched systems along the identified catchment boundaries. Correlation between the exit flows for the looped and branched systems were determined for several design storm events to validate subcatchment delineation boundaries. Correlations were generally high, with correlation coefficients above 0.97. Deviations occur mainly at low flows, for 6 out of 17 subcatchments.

2.2 Lag times in looped and branched networks

Concentration times in terms of time to peak and lag time were calculated for all subcatchments, both for the original looped network, including interactions between subcatchments and for the branched network, excluding interactions between the subcatchments. Calculations were done for two design storms with return periods of 5 and 10 years, with total rainfall volumes of 19.8 and 35.7 mm, peak values of 16.5 and 31.5 mm/h.

![Figure 1 – Lag times as a function of subcatchment area for all subcatchments; for original looped and for constructed branched networks](image-url)
In Figure 1 lag times are plotted as a function of subcatchment area for all 17 subcatchments. The results show that lag times vary from 10 to 65 minutes for subcatchment sizes between 0.3 and 7.8 ha. Lag times are short, 10-25 minutes, for catchments up to 2 ha, while for larger catchments they vary over a wide range, between 25-65 minutes. The values show that variation in catchment area size can explain only a part of variation in lag times ($R^2$-value 0.4).

Lag time values in Figure 1 for the looped and branched versions of the system differ more than 10% for 7 out of 17 subcatchments. This means that for these systems flow between subcatchments in the looped networks is not negligible and that subcatchment area per exit point varies during the storm event in the looped systems.

Figure 2 – Hydrographs of subcatchments for Scheemda North subcatchments, looped and branched network versions
In Figure 2 hydrographs are shown for all subcatchments of the Scheemda N system, for the looped and for the branched networks. The shape of the hydrographs reflects the influence of both catchment area and flow-path lengths, with more peaked hydrographs for small, concentrated catchments and flatter peaks and longer tails for larger, more extended catchments. Differences between the looped and branched networks occur especially at the start and in the tail of the event, see for instance hydrographs of subcatchments 2.3 and 2.6. Under these conditions, flow processes are determined by filling and emptying of the system and flow towards the wastewater pumping station, while under high flow conditions flow towards the exit points becomes dominating.

The “loopedness” of networks and the number of interconnections between subcatchments explain part but not all of the differences. In cases where subcatchment size varies during a storm event, lag times of hydrographs cannot be related to a single subcatchment area size. A bandwidth of subcatchment sizes could be used instead or lag time analyses should be limited to large, concentrated storm events where filling and emptying processes of the system have a relatively small influence.

In Figure 3, lag times are plotted as a function of pipe length per subcatchment. The results show that pipe length explains variation in lag times to a similar degree as catchment size area (R²-value 0.4). The results for time-to-peak as a function of catchment size or pipe length (not shown here) show that values for time-to-peak vary less between subcatchments. Since time-to-peak only reflects runoff delay during the start of the event, it is only influenced by flow variations during the filling process of the system. As a result, catchment size and pipe length explain less of the variance (R²-values of 0.24 and 0.25 respectively, for looped systems).

2.3 Relations between catchment characteristics and lag times, discussion

Catchment size has been hypothesized by several authors to be an important explanatory factor for response time variation (Schilling, 1991; Barron et al., 2011). The results in this study show that catchment size can explain only a part of the variation in lag times for the investigated small urban catchments in lowland areas. Lag time values found in this study are larger than values found in the literature, where lag times above 10 minutes are typically found for catchments larger than 100 ha (Berne at al., 2004), while in this study lag times above 10 minutes are found for catchments areas from 1 ha upwards. These longer lag times are likely to be explained by the flatness of the investigated catchments, typical for lowland areas, resulting in lower flow velocities and longer response times.
3 CONCLUSIONS

Lag times calculations for 17 small subcatchments in lowland urban drainage systems show that variation in catchment area size can explain only a part of variation in lag times between the subcatchments. Pipe length per subcatchment explains variations in lag times to a similar, low degree. The analysis also shows that for about half of the subcatchments lag time values are influenced by flow between subcatchments in the looped networks, especially during low flow conditions. This means that in looped systems subcatchment area per exit point varies during a storm event and lag time cannot be directly related to a single catchment characteristic.

4 REFERENCES


