Assessing characteristic time and space scales of in-sewer processes by analysis of one year of continuous in-sewer monitoring data

R. P. S. Schilperoort, J. Dirksen, J. G. Langeveld and F. H. L. R. Clemens

ABSTRACT

Long-term and high-frequency in-sewer monitoring opens up a broad range of possibilities to study (influences on) water quantity and quality variations. Using data from the Eindhoven wastewater system in The Netherlands both dry weather flow and wet weather flow situations have been studied. For approximately 160 dry weather days mean diurnal variations of flow and pollutant concentrations have been derived. For wet weather situations (= 40 storm events) peak load factors have been studied. Generally, peak load factors for all considered pollutant parameters are larger than one. Peak load factors for particulate matter are larger than for dissolved constituents. Also, the smallest catchment area consistently shows the largest mean peak factors and vice versa.

Key words | dry weather flow, in-sewer processes, monitoring data, peak factors, wastewater composition, wet weather flow

INTRODUCTION

In the last decade wastewater monitoring equipment has seen a drastic development, which enables continuous and high-frequency monitoring over long time periods. This shifts the focus in monitoring projects from collecting samples and laboratory labour to data validation and subsequent data analysis. For instance, Mourad & Bertrand-Krajewski (2002) and Liefting & Langeveld (2008) describe in detail the required data validation steps, resulting in a set of validated data. This paper focuses on the subsequent data analysis and interpretation to obtain information on characteristic time and space scales of in-sewer processes in urban wastewater systems. For this, a 19-month dataset on wastewater quantity and quality parameters was available from the Eindhoven area in The Netherlands. Distinct analyses have been made for dry weather flow (DWF) and wet weather flow (WWF) situations, focusing on differences due to catchment characteristics and inter-event variations.

METHOD

The Eindhoven wastewater treatment plant (WWTP, 750,000 population equivalents) treats the wastewater from ten municipalities divided over three catchment areas that are very different in size and character, and each has a separate inflow to the WWTP; see Figure 1. Wastewater from Eindhoven Stad (ES, municipality of Eindhoven) accounts for approximately 50% (or 17,000 m³/h) of the hydraulic capacity and discharges directly to the WWTP. The other nine (much smaller) municipalities are each connected to one of the two wastewater transport mains, one to the north (Nuenen/Son or NS, 7 km in length) and one to the south (Riool-Zuid or RZ, 32 km in length), accounting for respectively 7% (3,000 m³/h) and 43% (15,000 m³/h) of the hydraulic capacity. An elaborate description of the studied wastewater system can be found in Schilperoort (2011).

At each of the three inflows into the WWTP (locations ‘A’ in Figure 1) on-line sensors have been installed that measure concentration values of wastewater quality parameters total suspended solids (TSS), chemical oxygen demand (COD) and filtered COD (CODf) (dissolved fraction) at an interval of 2 min. The used sensors are Ultraviolet–visible (UV/VIS) spectrometers (type spectro::lyser by manufacturer s::can, Austria) that relate ultraviolet and visible light absorption to the aforementioned quality parameters. A suffix -eq
indicates that measurement results constitute an equivalent value based on optical measurements instead of 'standard' laboratory analyses. For a detailed description of the sensor, refer to e.g. Langergraber et al. (2003).

All three UV/VIS sensors have been installed in their own by-pass installation. Each installation is fed by a 6 L/s shredding pump that is positioned in a pump suction chamber of the WWTP influent pumping station; see Figure 2. The pumps are installed after the 25 mm bar screens to prevent too frequent clogging of the by-pass pumps. Their suction mouths are located at a height of approximately one third of the normal DWF target water level, which is in accordance with ISO (1992) to obtain a value representative of the solids present in the wastewater flow.

The UV/VIS sensors have been calibrated per sensor and per parameter to the local wastewater matrix by means of two calibration campaigns: one for DWF conditions (24 hourly samples on a dry weather day) and one for WWF conditions (10 hourly samples during one storm event). Using the reference values (grab samples, subsequent standard laboratory analysis), a linear regression model has been derived that corrects the sensor measurement results (on manufacturer's settings or 'global calibration') for the local wastewater matrix ('local calibration'); see Figure 3. Despite known matrix variations during dry weather conditions (e.g. Gruber et al. 2005; Maribas et al. 2008) as well as (large) inter-event variations for wet weather situations (e.g. Stumwöhrer et al. 2003), budget constraints have limited the calibration campaigns to a single dry weather day and a single storm event. This should be appreciated when studying the measurement results.

Two-minute interval flow rates at all three WWTP inflows have been derived using monitoring data from full-pipe electromagnetic flow sensors installed at the discharge lines of the WWTP influent pumps. The combination of the UV/VIS and flow data yields pollutant loads per 2 min for the aforementioned pollutant parameters. In total, a 19-month (1 April 2007 – 1 November 2008) dataset is available for all parameters. After extensive data validation the data sets have been reduced to a net time-span of approximately 1 year.

RESULTS AND DISCUSSION

Dry weather conditions

DWF days have been selected using precipitation data. The applied definition of a DWF day is: 'if during a 2-days time-span in total less than 0.5 mm of precipitation has been recorded the last day can be considered a DWF day'. This way, around 200 DWF days have been identified. Per 2 min time-step mean values are calculated, then normalised with respect to the overall DWF mean flow value and plotted in Figure 4. The results constitute the mean DWF patterns of wastewater flow from the three catchment areas to the treatment plant.

For all three catchments a clear diurnal variation can be observed. Compared with typical DWF patterns (e.g. Metcalf & Eddy 2003) the patterns are shifted in time due to the relatively long wastewater travel times that differ per catchment area. As expected, peak factors reduce with increasing catchment size. Peak values are of the same order as for catchment areas of similar sizes (e.g. CIRIA 1998; Krebs et al. 1999). Analysis of data distribution at the six peak moments (maximum and minimum values for the three DWF patterns) has yielded normal distributions in five cases; only data at the minimum peak of Nuenen/Son flow data are lognormally distributed, which might be due to infrequent and relatively large industrial discharges during the night.

For the same dry weather days mean DWF patterns for catchment Eindhoven Stad have been plotted for pollutant parameters TSS, COD and COD (and flow Q for comparison) in Figure 5. DWF pollutant patterns are based on
fewer days than for flow (79 for COD$_{eq}$, 85 for TSS$_{eq}$ and 113 for COD$_{eq}$ versus 158 for Q) as more data were discarded during data validation. Pollutant concentrations show a similar diurnal variation to flow. However, peaks are less pronounced (closer to one, especially for night-flow) and occur slightly later. Suspended compounds show the largest DWF variation over a day associated with the variation in flow values. Pollutant peak values may be less pronounced, but – as indicated by results in the box plot – the variation around mean values is larger than for flow. Diurnal patterns for pollutants and flow that are similar in shape are observed for Eindhoven Stad and Nuenen/Son, but not for Riool-Zuid. Although for Riool-Zuid a regular diurnal DWF pattern was observed (see Figure 4), Figure 6 shows an odd COD$_{eq}$ DWF pattern. A clear night minimum is lacking and around noon a sharp increase in particulate matter is observed. After ample consideration, this atypical pollutant pattern has been attributed to the arrival of centrate from the WWTP sludge processing installation. This installation (situated 7 km further upstream in the system) is operated 24 h per day, but centrate is only discharged to the sewer system during working hours. At 08h00 every morning the complete night stocks are discharged, arriving at the WWTP around noon.

**Wet weather conditions**

During the 19-month monitoring campaign a large number of storm events have occurred. To illustrate the short-term fluctuations in concentration levels of pollutants in WWTP
influent as a result of storm events, Figure 7 gives an example for catchment area Eindhoven Stad. In the morning of 12 June 2008 a 16 mm storm event causes flow to increase by a factor $\sim 6$. The moment flow rises above DWF levels large peaks in mainly particulate matter concentrations ($TSS_{eq}$ and $COD_{eq}$) can be observed. Approximately 7 h into the storm event all parameter concentrations have reduced by a factor $\sim 2$ with respect to pre-storm DWF values. After precipitation ceases, flow values return to DWF values within a time-span of roughly 6 h. Pollutant concentrations, however, recover more slowly to pre-storm DWF levels. At the end of the event $TSS_{eq}$ and $COD_{eq}$ concentrations are still below normal DWF levels and continue to recover.

Even though concentration levels fall during the storm event, the relatively larger increase of flow rates leads to an overall increase in total loads discharged to the WWTP from the catchment area; see Figure 8. The figure shows flow, $COD_{eq}$ loads and the 12 and 24 h moving average of loads (all normalised to the mean DWF value). It can be observed that directly after the onset of the event $COD_{eq}$ loads briefly increase to roughly 10 times the mean DWF load. Considered at larger time scales, the variation of pollutant loads during the storm event is more gradual and peak load factors (PLF, i.e. the maximum attained normalised load during a storm event) are hence smaller. This is illustrated in the figure with the application of symmetrical moving average filters with spans of 12 and 24 h. For the parameter $COD_{eq}$ this yields a $PLF_{12}$ of 4.8 and a $PLF_{24}$ of 3.5. The $PLF_{24}$ is an interesting parameter for WWTP performance and future WWTP design criteria (Langeveld 2004). Essentially, it expresses the arriving load as a multiple...
of normal DWF load (which – normalised to DWF mean and averaged over 24 h – consistently equals one). The PLF enables easy comparison of peak loads from different catchments without the need to define a storm event.

In total, per catchment area and per pollutant parameter approximately 40 PLF24 have been calculated. Results are given in Figure 9. For all three catchment areas and for all three parameters mean PLF24 values are larger than one. This means that for a ’mean storm event’ the arriving pollutant load over 24 h from all inflows is systematically larger than during dry weather. The magnitude of this ’mean storm peak load’ varies with parameter and catchment area. The largest mean PLF24 values are found for TSSeq (2.0–4.3), followed by parameters CODeq (1.7–3.3) and CODf eq (1.6–2.3). This suggests that during wet weather conditions the additional discharge of suspended solids is consistently larger than for dissolved compounds. The smallest catchment area (Nuenen/Son) shows the largest mean peak factors whereas values are smaller for Riool-Zuid and Eindhoven Stad, the largest catchments. This contradicts earlier research (Kafi et al. 2008) where no significant variability between catchments of different sizes could be observed. For parameter CODf eq the catchment size effect is less pronounced than for parameters TSSeq and CODeq.

The smallest PLF24 values in Figure 9 are equal or close to one. In other words, for ’small storm events’ arriving pollutant loads over 24 h are on the same order of magnitude as mean dry weather loadings. For relatively large storm events (i.e. the largest values in Figure 9) 24-h
loadings can become much larger than mean DWF values: for parameter TSSeq a factor 3–6 for large areas such as Riool-Zuid and Eindhoven Stad and up to a factor 10 for area Nuenen/Son. For parameters CODeq and CODfeq these values are smaller, but remain much larger than any dry weather variation.

**CONCLUSIONS**

Long-term and high-frequency in-sewer monitoring opens up a broad range of possibilities to study (influences on) water quantity and quality variations. Based on data from the Eindhoven area, both DWF and WWF situations have been studied. For dry weather a clear diurnal variation of flow can be observed for all three studied catchment areas. At peak moments, flows are often normally distributed. For two catchment areas associated pollutant concentrations show a similar diurnal variation to flow. For one area, however, a specific catchment characteristic causes an odd diurnal variation of pollutant concentrations. For wet weather situations the peak load factor (i.e. the largest value of the 24 h moving average of normalised loads during a storm event) is an interesting parameter for WWTP performance and WWTP design criteria. For all three catchment areas, TSSeq mean and individual peak load factors are the largest, followed by CODeq and CODfeq. The smallest catchment area consistently shows the largest mean peak factors, and the largest and most compact catchment the smallest.

**ACKNOWLEDGEMENTS**

The authors would like to acknowledge Waterschap De Dommel for the use of their data in this project. We thank E. Liefting of Royal Haskoning for his assistance in data processing.

**REFERENCES**


First received 9 December 2011; accepted in revised form 26 January 2012