A New Empirical Sewer Water Quality Model for the Prediction of WWTP Influent Quality

Jeroen LANGEVELD[1,2*], Remy SCHILPEROORT[1], Petra VAN DAAL[2,3], Lorenzo BENEDETTI[4], Youri AMERLINCK[5], Jarno DE JONGE[6], Tony FLAMELING[6], Ingmar NOPENS[5], Stefan WEIJERS[5,6]

[1]Royal Haskoning DHV, P.O. Box 151, 6500 AD, Nijmegen, The Netherlands
[2]Delft University of Technology, PO Box 5048, Delft, The Netherlands
[3]Witteveen+Bos, P.O. Box 233, 7400 AE Deventer, The Netherlands
[4]WATERWAYS srl, Via del Ferrone 88, 50023 Impruneta, Italy
[5]BIOMATH, Department of Mathematical Modelling, Statistics and Bioinformatics, Ghent University, Coupure Links 653, 9000 Gent, Belgium
[6]Waterschap De Dommel, P.O. Box 10.001, 5280 DA, Boxtel, The Netherlands
[*]Corresponding author
Email: j.g.langeveld@tudelft.nl

ABSTRACT
Modelling of the integrated urban water system is a powerful tool to optimise wastewater system performance or to find cost-effective solutions for receiving water problems. One of the challenges of integrated modelling is the prediction of water quality at the inlet of a WWTP. Recent applications of water quality sensors have resulted in the availability of long time series of sewer water quality and WWTP influent quality. This time series contains a lot of information on the response of sewer water quality to, for example, storm events. This allows the development of empirical models to predict sewer water quality. This paper proposes a new approach for water quality modelling, which uses the measured hydraulic dynamics at the influent of the WWTP to derive the (measured) influent water quality. This model can then be used as a WWTP influent generator using either measured or simulated influent hydraulics as input.

KEYWORDS
Sewer system, empirical model, influent generator, water quality modelling

INTRODUCTION
Modelling of the integrated urban water system is a powerful tool to optimise wastewater system performance or to find cost effective solutions for receiving water problems (Benedetti et al., 2013a). One of the weaknesses of integrated modelling is the water quality modelling in sewer systems, due to the limited knowledge on the physical-chemical, biological and transport processes occurring in sewer systems (Bertrand-Krajewski, 2007). Especially sediment transport is not very well understood and not very successfully reproduced in deterministic models. This is partly due to the fact that it is currently not possible to get enough data on the initial sewer sediment conditions throughout an entire sewer network. As a consequence, a lot of effort has been put in the development of regression models, which are validated against monitoring data. A recent successful example of this approach is given by Dembélé et al. (2011), who developed an empirical model for stormwater total suspended solids (TSS) event mean concentrations with rainfall depth and antecedent dry weather period as input variables. These empirical relations, that are valid at a combined sewer overflow (CSO) or storm sewer outfall (SSO), however, are not suitable for

the prediction of wastewater treatment plant (WWTP) influent quality, as these models do not predict the influent quality during dry weather flow (DWF).
Recent applications of water quality sensors have resulted in the availability of long time series of sewer water quality and WWTP influent quality. These time series contain a lot of information on the response of sewer water quality to e.g. storm events. This allows the development of empirical models to predict sewer water quality at the inlet of a WWTP, such as for example the one by Talebizadeh et al. (2014). They use a mix of statistical and conceptual modeling techniques for synthetic generation of influent time series based on a periodic multivariate time series model for the influent in DWF conditions and a two-state Markov chain-gamma model for rainfall conditions. The main drawback of this approach is that the errors in the hydrologic runoff and hydraulic sewer model cumulate. In order to overcome this drawback, a new approach is developed and presented in this paper, which uses the measured hydraulic behaviour at the influent of the WWTP to derive the (measured) influent water quality. This model can then be used to predict WWTP influent water quality using simulated influent hydraulics as input.
This paper describes the development of this new model for the WWTP Eindhoven in the Netherlands, with flow and water level as the input variables. The paper also discusses the transferability of the developed concept to other locations.

METHODS AND MATERIALS

System description: the Dommel River IUWS

The Dommel is a relatively small and sensitive river flowing through the city of Eindhoven (The Netherlands) from the Belgian border (South) into the river Meuse (North), receiving discharges from the 750,000 PE wastewater treatment plant (WWTP) of Eindhoven and from over 200 combined sewer overflows (CSOs) in 10 municipalities. In summer, the WWTP effluent equals the base flow of 1.5 m^3/s of the Dommel River just upstream the WWTP. The Dommel River does not yet meet the requirements of the European Union Water Framework Directive (WFD). The water quality issues to be addressed are dissolved oxygen (DO) depletion, ammonia peaks and seasonal average nutrient concentration levels (Weijers et al. 2012). Benedetti et al. (2013b) describe the set of measures required for compliance with the WFD and the methodology applied to derive them as developed in the KALLISTO project.

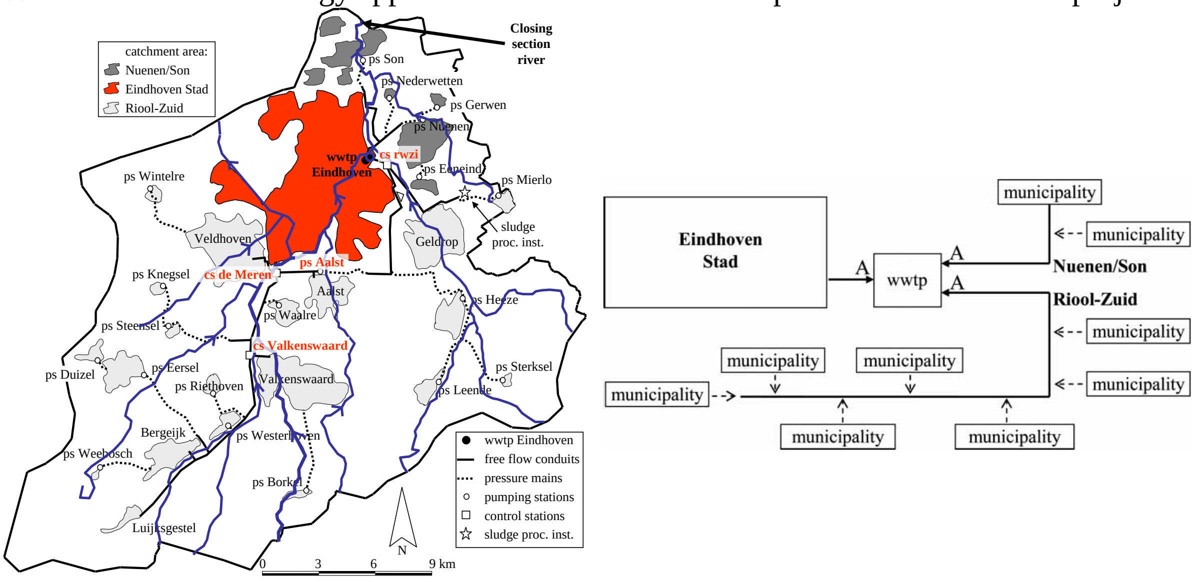

Figure 1. Wastewater system of Eindhoven (left) and its receiving streams and schematic lay out of the wastewater system (right)

The 10 municipalities are divided over three catchment areas that are very different in size and character, each having a separate inflow to the WWTP (see Figure 1). Wastewater from Eindhoven Stad (ES, municipality of Eindhoven) accounts for approximately 50% (or 17,000 m^3/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 m^3/h) and 43% (15,000 m^3/h) of the hydraulic capacity. An elaborate description of the studied wastewater system can be found in Schilperoort (2011).

Monitoring network

At each of the three inflows into the WWTP (locations 'A' in Figure 1) on-line UV/VIS sensors have been installed that measure equivalent concentration values of wastewater quality parameters: total suspended solids (TSS_{eq}), chemical oxygen demand (COD_{eq}) and filtered COD ($CODf_{eq}$) (dissolved fraction), at an interval of 2 min. In addition, flow has been recorded every minute at these locations and ammonia (using Amtax sensors) at the Eindhoven city and Riool-Zuid catchments. The monitoring data have been validated prior to data analysis, using basic validation routines (Bertrand-Krajewski and Muste, 2008).

Data analysis

In earlier work (Schilperoort et al., 2012) a part of this dataset has been used to study the dynamics of wastewater composition. This resulted in well described diurnal patterns during DWF, see figure 2 (left) and typical dynamics during WWF (figure 2 (right). For WWF, it has been observed that the concentration levels of the wastewater show a typical pattern during a storm event: a short period called 'onset' of the storm event, with an increased concentration level for particulate matter but not for dissolved matter, a longer period called 'dilution', where dilution of both dissolved and particulate matter takes place, and 'recovery', a period where dissolved and particulate matter slowly return to DWF levels.

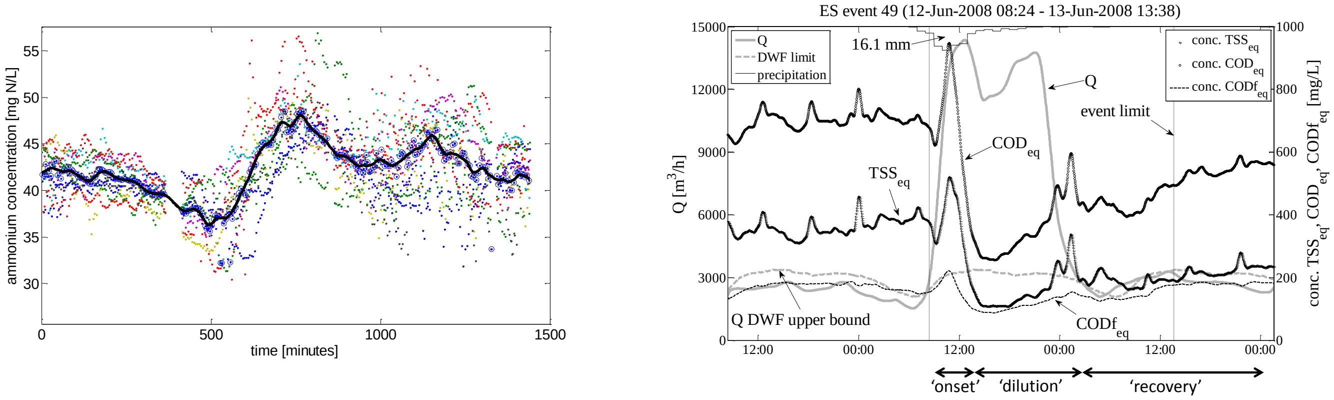

Figure 2. NH4 dry weather flow diurnal pattern (black line) based on the average values per 5 minutes (blue circles) of the values of 10 dry weather days (coloured dots; 1440 minutes in a day) (left) and WWF dynamics (right)

Model development

In the model under dry weather conditions both flow and water quality parameters show a 'typical' dry weather flow pattern. A DWF pattern is assumed for water quality as long as flow values indicate dry weather conditions. For flow values, the upper limit for dry weather conditions is set at the 95th percentile of the values collected during dry weather; if this limit is exceeded wet weather flow is assumed to begin. During wet weather, the model superimposes a number of processes to the DWF pattern for water quality to mimic onset, dilution and recovery. This allows the development of a model with sufficient predictive power to be able to evaluate the impact of RTC actions in the wastewater system.

For solutes, 3 processes have been added to the DWF basic process; for particulate matter one more process is added to the model for solutes.

Process 1, the basic process for all parameters, is the DWF pattern for water quality, derived by averaging high-frequency monitoring data collected during multiple dry weather days (see figure 2, left).

Process 2 mimics dilution and is based on the ratio between the actual flow (Q_{actual}) and the flow during DWF at that time of the day at the location of the WWTP inlet works (Q_{DWF}). The wastewater concentration is calculated using formula (1):

$$C_{WWF} = C_{DWF} * a1 * Q_{DWF}/Q_{actual} \quad (1)$$

with C_{WWF} = calculated concentration during wet weather, and C_{DWF} = the concentration during DWF conditions at that time of the day. The factor a1 (-) is introduced to allow adjustment to the dilution rate if necessary. A value of 1 for factor a1 indicates that the dilution is exactly inverse to the increase in flow; a value of a1 larger than 1 would impose an increase in pollutant loads during the event, which could be necessary to account for pollutant contributions originating from in-sewer stocks.

Process 3 reproduces restoration, which describes the gradual return of concentration values to DWF values after the storm event. Based on the analysis of the available dataset, restoration is assumed to be a linear process at rate a2 (mg/(l.s)) until the concentration returns to the DWF value. During the restoration phase, the concentration is calculated by:

$$C_{WWF\,(t+1)} = C_{WWF(t)}*(1+a2)*dt \quad (2)$$

Process 4 regards dilution and restoration for small events, as it was found that the relation between flow and concentration levels differs very much between small and large storm events. Processes 2 and 3 can be applied for large storm events: events during which not only flow increases, but also the water level in the influent pumping station increases above the DWF threshold value. Process 4, on the other hand, is to be applied for small storm events for which the water level in the influent chamber does not rise above this level. These are typically relatively small, low intensity storm events, where the inflow is less than the available pumping capacity (which is equal to an interceptor capacity of 0.7 mm/h or 7 m^3/ha). Process 4 describes the concentration profile as a fixed-shape triangle, where dilution takes place at a fixed rate a3 (mg/(l.s)) during 13 hours and recovery at the same rate a3 (mg/l/s) during the next 13 hours.

Process 5 describes a first flush in concentration levels of particulate material (see figure 2, right). This initial peak increases the concentrations during the first stage of storm events, before dilution becomes the dominant process. Process 5 is modelled as a triangle that causes an instant increase of the COD concentration by 600 mg/L at the onset of the event, decreasing with a fixed rate a4 (mg/(l.s)) as long as the flow exceeds a threshold value (referred to as process 5a) and a fixed rate a5 (mg/l/s) as soon as the flow does no longer exceed the threshold value, referred to as process 5b).

The measured hydraulics, in this case the flow and water level in the influent pumping station, are used to determine which of the described processes should be activated in the model. The procedure developed is shown in figure 3, using the following checks:

Check 1. If the measured Q(t) exceeds the 95^{th} percentile value of Q_{DWF} at that time of the day, than the period that Q(t) exceeds Q_{DWF} is denoted as event of type 1.
Check 1 identifies all events with a flow exceeding the typical Q_{DWF}. This could be due to storm events, but also due to anomalies in the data or in pumping behaviour. In order to filter them, check 2 is defined as:
Check 2. An event is considered an event of type 2 if Q_{max} during the event is higher than a given threshold or if the total volume of the event exceeds the expected DWF volume.
In order to be able to discriminate between a large and a small storm event, check 3 is introduced:
Check 3. An event is considered a big storm event, i.e. event of type 3, only if the water level in the influent chamber exceeds a threshold.
This occurs only if the sewer system starts filling during bigger storm events exceeding the pumping capacity of the WWTP.

Check 1.	$if\ Q(t) \le Q_{DWF} \rightarrow DWF$	Activate process 1 (DWF mode)
Check 2.	$if\ Q(t) < Q_{Threshold} \cup if\ V_{event} < V_{Threshold} \rightarrow DWF$	Activate process 1 (DWF mode)
Check 3.	$if\ h(t) \le h_{Threshold} \rightarrow event\ type\ 2$	Activate process 1 (DWF mode) + activate process 4 (dilution and restoration)
	$if\ h(t) > h_{Threshold} \rightarrow event\ type\ 3$	Activate process 1 (DWF mode) + activate process 2 (dilution) + activate process 5a (for particulate matter)
	$if\ h(t) \le h_{Threshold} \cap if\ h(t-1) > h_{Threshold} \rightarrow end\ of\ event\ type\ 3$	Activate process 1 (DWF mode) + end process 2 (dilution) + process 5a (part. matter) + activate process 3 (recovery) + process 5b

Figure 3. Selection of water quality processes using information on hydraulics

Model calibration
The model was calibrated by minimising the difference between the model and the monitoring data for half of the dataset. This calibration was performed manually, as this allows to account for periods with low data quality in the dataset of measured concentrations (see figure 4). Automatic calibration would require a very strict prior data analysis and validation, possibly rejecting periods in the monitoring data where the dynamics of the measured signal still give information on the process dynamics, despite incorrect absolute values.

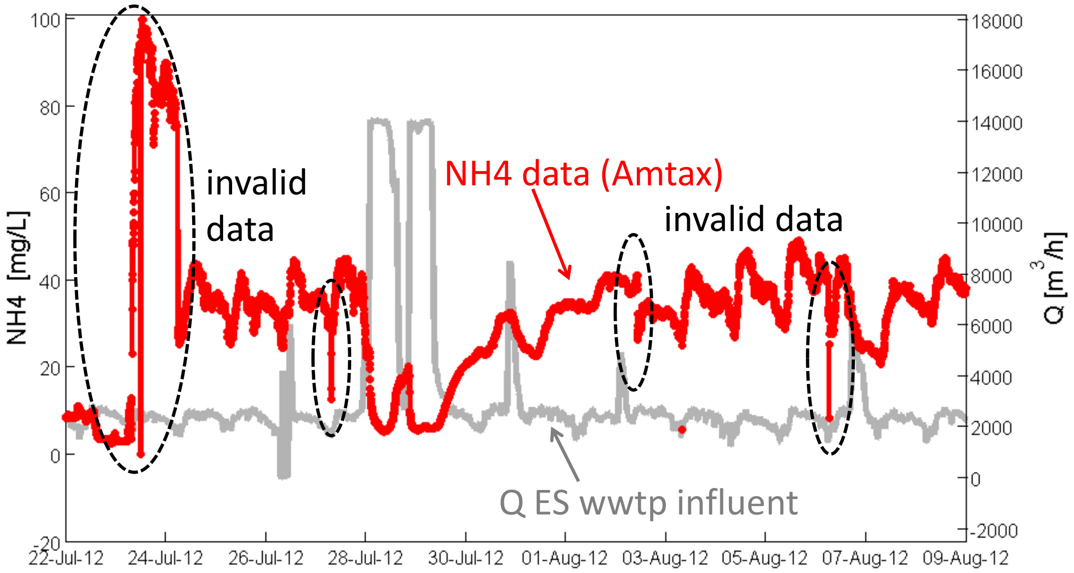

Figure 4. Example of quality evaluation of monitoring data

RESULTS AND DISCUSSION

Figure 5 shows the resulting predicted water quality and the measured water quality for ammonium in the WWTP influent. The results show that the dynamics in the model (solid black line) and the monitoring data (red dots) show an overall good agreement in terms of dynamics and values. In the monitoring data, dilution starts a little bit earlier than in the model. This can be overcome by adjusting the threshold value for the flow. As this has adverse effects on the long-term performance of the model, this adjustment has not been made.

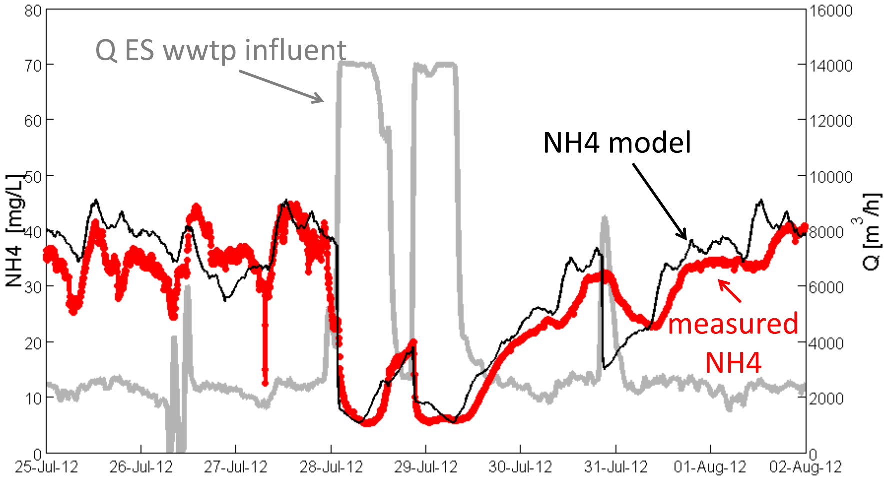

Figure 5. Model vs. monitoring data: ammonium concentration in the WWTP influent

The most important period with respect to the loading of the WWTP is the period with high influent flows. During this period, the influent model is based on the dilution process described in formula (1). The factor c1 was kept at a value of 1, meaning that the dilution of the influent Q_{DWF}/Q_{actual} is perfectly reciprocal to the increase in influent flow. This means that the total load in the influent remains at DWF level, while at the same time a significant load can be emitted via the CSOs. During CSO events, the total load from the sewer system discharged via the WWTP influent + CSO discharges typically exceeds the DWF load + runoff contribution during this event. This additional load is attributed to the contribution of in-sewer stocks (Schilperoort et al., 2012).

State of the art sewer models account for the sewer stocks by adding processes for sediment transport. However, for solutes like ammonium, these models simply calculate the ammonium concentration by mixing the DWF and rainfall runoff. As the DWF typically has a flow in the order of 1 m^3/ha/h, whereas the storm runoff can be as high as 200 m^3/ha/h, during CSO events, a dilution of over a factor of 100 with storm water is not unusual.

Given the typical concentration levels for ammonium of 60 mg N/l in DWF and between 1 and 2 mg N/l in storm runoff (Langeveld et al., 2012), the only way these models can calculate realistic ammonium concentrations in the influent is by adjusting the ammonium concentration in storm runoff to unrealistic values, varying by event.

As the proposed influent model implicitly accounts for in-sewer stocks, it gives a much more robust prediction of the influent quality than traditional sewer water quality models.

Figure 6 shows the results for the COD model. As expected, the model fit is less well than the model for ammonium, as the modelling of suspended solids has been demonstrated to be much more difficult than the modelling of solutes. On the other hand, the nitrification performance of a WWTP is more affected by fluctuations in the concentration of ammonium in the influent than on the concentrations of COD in the influent. This means that the requirements for modelling COD are in this case (the focus in Eindhoven is to reduce effluent ammonium peaks) less stringent than for ammonium (Langeveld et al., 2003) and that both empirical models presented meet the requirement (Langeveld et al., 2003).

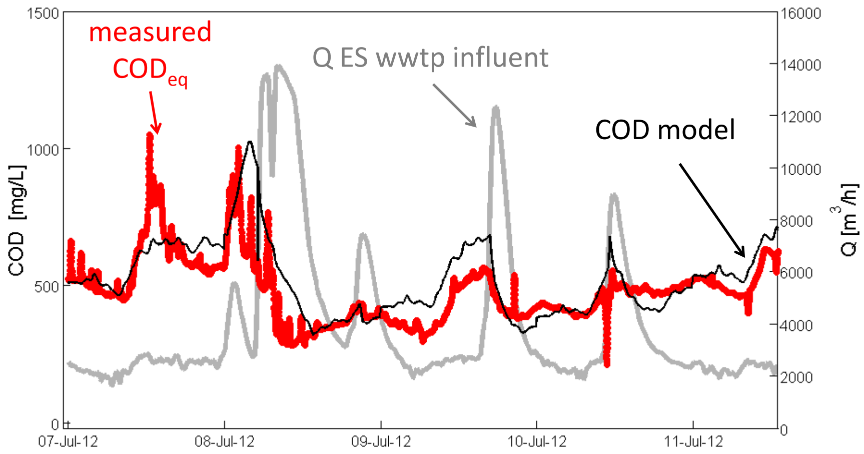

Figure 6. Model vs. monitoring data: COD_{total} in the WWTP influent

Transferability of the concept

Figure 5 and 6 present the results for the influent chamber receiving wastewater from the 'Eindhoven city' catchment. In figure 7, the results are shown for the Riool-Zuid catchment (the light grey catchments in figure 1, left), which has a very different structure compared with 'Eindhoven city' (the red catchment in figure 1, left). As expected, it was necessary to adjust the parameters a2 and a3 to adapt to the system characteristics to get a reasonable fit for this catchment. There was no need to change the model structure, however, which implies that the model is transferable to other catchments. The main difference between the two catchments is the double dilution dip during storm events in the Riool-Zuid catchment. This is likely caused by a difference in transport times for two areas in this catchment, which causes the concentrations to drop for a second time during a storm event, at the moment the influent flow starts to reduce towards DWF values.

This effect can be mimicked by dividing the Riool-Zuid catchment in two catchment basins, and to add the transport time of the 32 km long transport sewer to one of the basins. However, as the error made in the total influent load during this part of the storm is relatively small due to the low influent flows, this adjustment is not considered necessary.

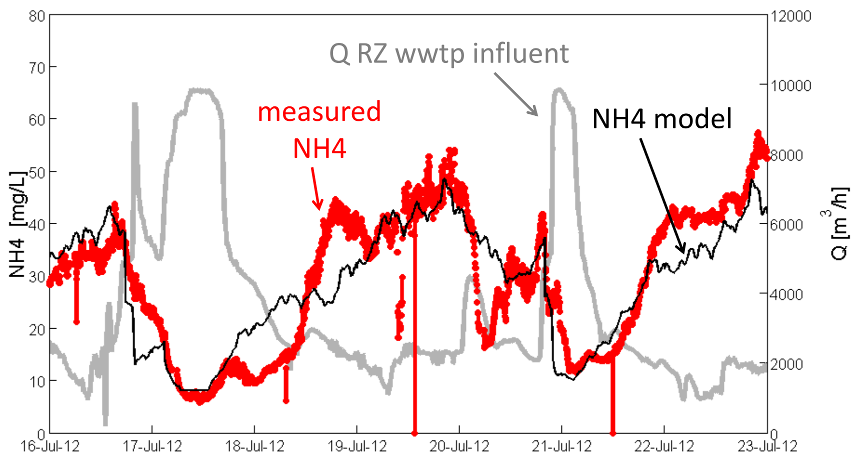

Figure 7. Model vs. monitoring data: ammonium concentration in the WWTP influent catchment Riool-Zuid

CONCLUSIONS

Modelling of influent quality is an increasingly important tool to enable WWTP models to optimise the performance of WWTPs during wet weather. The main issue in modelling wastewater quality during storm events is to account for in sewer stocks, which have a varying contribution to the wastewater quality. Neither traditional sewer water quality models nor the available influent generators are capable of adequately addressing this issue. The new empirical model proposed in this paper is based on a detailed study of the observed water quality and predicts it by combining a number of actual processes, such as DWF, dilution, restoration and first flush. Overall, the model shows to be able to accurately predict ammonium concentration, which is a solute substance, and reasonably predict COD concentration, which is to a large extend associated with particles.

The model structure has been demonstrated to be transferable to a catchment with very different characteristics. The model parameter values can be considered as defined by the system characteristics.

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