An integrated water quality monitoring network

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Abstract
The quality of predictions from simulation models substantially depends on the quality of the input and reference data. In the field of urban drainage modelling integrated models are used which demand data from different sources. Depending on the goal of the study different requirements with regard to data quality and time resolution exist. Often a major portion of the overall study workload has to be contributed towards data mining and data preparation. A lack of dynamic data can often be observed. This is especially negative if transient pollution events are in the focus of the study.
A research project conducted in Austria focused on the development, installation and operation of an integrated water quality network applicable for sewer networks to surface water. The paper gives an overview on practical aspects of the network operation and the used sensor technology. It is shown that today's sensor technology allows continuous monitoring of water quality with acceptable maintenance demand. Some improvement is still required with respect to the trueness of the measurement signals. Within this respect the value of the availability of continuous recordings over long periods has to put in relation with results from short term labour and cost intensive sampling and laboratory based monitoring campaigns with probably higher accuracy.

Keywords
Continuous sewer monitoring, monitoring networks, river water quality monitoring, spectroscopy

INTRODUCTION

Data for integrated modelling
One essential base for each simulation exercise is input and reference data. Depending on the goal of the simulation study different requirements with respect to time resolution and trueness of data exist.
Not at last due to EC-Water Framework Directive an integrated approach on catchment scale with respect water quality management will be mandatory in the future. Integrated urban water modelling is an important part of this integrated approach; management and minimisation of pollution discharges from sewer networks and point sources are two important tasks of urban water management (Frehmann et al., 2002).
A major challenge with respect to the setup of integrated models is data mining and data preparation. Often data has been collected by different authorities with different methods and stored in different formats. Special monitoring campaigns have been conducted to address specific aspects; often the question about the general validity and applicability of the results of such short term monitoring exercises remains.
A lack of dynamic data can often be observed, especially continuous measurements over longer periods. Especially, if transient pollution events (Beck, 1996) are in the focus of the investigations, good quality dynamic data are of utmost importance. For example, in combined sewer networks the determination of the discharge loads from combined sewer overflows is a challenging task. Some cities have installed flow measurements in sewer networks – calibration and validation of such measurements can be troublesome. A vast number of boundary conditions (sewer inclination, stormwater flow, duration of dry weather periods, …) have an effect on the concentration of the discharged pollutants.

One reason for the lack of long-term dynamic observations is that up to recently the available sensor technology was not suited for a continuous application in raw wastewater and sewer networks. Within the last years some sensors became available which are potentially applicable in sewer networks, but also for other important applications in the filed of integrated water quality monitoring.
A research project has been conducted in Austria, which focused at an integrated approach for a water quality monitoring network. Three monitoring stations were included in the monitoring network, each covering a specific research task: Discharge loads combined sewer overflows, process optimisation of WWTP´s and surface water quality monitoring downstream of a large WWTP.

Continuous water quality monitoring

Continuous water quality monitoring is still a challenging task due to the high number of adverse boundary conditions. This is especially true for integrated investigations, as opposed to a single spot monitoring. The following Table 1 gives a brief overview of general and application specific tasks, which have to be considered for design and operation of water quality monitoring networks.

Table 1: General and application specific tasks for design and operation of water quality networks

General – Data handling				
Uniform data format Data recording reliability Data transfer reliability Data quality assurance Data evaluation methods				
General – Sensor operation				
Sensor operation stability Sampling location representativeness Sampling location accessibility User friendliness of sensor operation				
Application specific				
Sewer	**WWTP**	**Surface water**	**Ground water**	**Drinking water**
EX certification of sensors	Sensor fouling	Water level variations	Concentration gradients	Hygienic standards
Flow measurement: Complicated channel geometry, limited number of flow measurement methods applicable	Increased risk of sensor damage due to aggressive media	Flow speed variations	Lower detection limit of applied sensors	Lower detection limit of applied sensors
Increased risk of mechanical damage of sensors	Matrix variations	Increased risk of mechanical damage of sensors	Power supply	
Increased risk of clogging of sampling hoses		Vandalism		
Sensor fouling		Lower detection limit of applied sensors		
Increased risk of sensor damage due to aggressive media		Power supply		
Matrix variations				
Power supply				

When a water quality monitoring network is designed the first question is to decide which parameter will be measured at which location using which measurement method – or subsequently which sensor. Often practical aspects such as accessibility to or infrastructure of the measurement location (power supply, water or pressurized air for automatic cleaning systems) have a considerable impact on the network design. Maintenance demands, power consumption and required auxiliary equipment of the applied sensors strongly influence the selection of measurement

location. In sewer networks often EX-certification of the installed sensors is mandatory, which significantly reduces the number of applicable sensors.
Special consideration needs the installation of the sensor, since each sensor also represents an obstruction in a sewer channel. Risk of sensor or channel clogging and sensor damage due to mechanical impact need to be especially considered.
In WWTP´s sensor fouling and the influence of dynamic variation of the wastewater composition on the trueness of the measurement signals are two important aspects.
For surface water quality monitoring also the question of sensor installation is very important. In rivers, accessibility to the sensors under varying water level conditions and protection of the installation against debris (especially during high flow conditions) need special consideration.

MATERIAL AND METHODS

The modular water quality monitoring station

For the above mentioned research project water quality monitoring stations were designed in a modular form. The same sensor types were applied in each station. Compact in-situ sensors were preferred over analysers requiring sample preparation.
A submersible spectrometer was used for indirect measuring organic of organic compounds (COD, TOC, BOD). Some experience with this instrument has been collected during tests in WWTP´s (Winkler et al., 2002) before the start of the project. These tests showed that the instrument can be operated also in raw wastewater over longer periods with only little maintenance demand. The cleaning system with pressurized air usually worked reliably. The instrument showed a high precision but a limited trueness depending on the magnitude of variations of the wastewater composition. For COD-total a 95%-confidence interval in the range of ± 60 mg_{COD}/l was found; the confidence interval was almost constant for the entire COD-concentration range. This resulted in a relative error of approx. ± 15-20 % for the upper measurement range (> 300 mg_{COD}/l), but a relative error of up to 50 % in the lower measurement range.
ISE-sensors were applied for in-situ measurement of nitrate and ammonium. Also these sensors have been tested in different applications in WWTP´s (Rieger et al., 2002) before the start of the project. For example, an ISE-ammonium-sensor was applied for eight months in the effluent channel of a primary clarifier tank. The result of the test was that ISE-sensors can be operated with relatively low maintenance need even in raw or mechanically treated wastewater. The cleaning system (first water, later pressurized air) worked reliably. Considerable effort is required for sensor calibration; the suitable calibration method is depending on the ratio of the concentration of the measurement ion (for example $NH4^{+}$, $NO3^{-}$) to the variation of the concentration of disturbance ions (for example K^{+}, Cl^{-}).

Sensor installation

Sensor installation can be considered as part of the measurement method, since if is of utmost importance that the sensor is located at a representative sampling spot under all conditions occurring at the measurement location. For measurements in sewer networks and rivers this means that the issue of highly varying water level and flow velocity has to be addressed.
For measurements in sewer networks floating installations seem to be most appropriate. With such an installation the sensor is always located in the top water layer – and subsequently measures the water quality which is discharged at the overflow weir during stormflow conditions. Also the risk of clogging is minimized since the sensor is not in an entirely fixed position and caught debris can be released due to sensor movement.
At the installation of the UV-VIS-spectrometer in the CSO-chamber (Figure 1) in Graz some problems with accumulation of debris during low flow periods (night hours) were experienced in the beginning. Since the installation of moveable steel ropes (deflection pulleys) this problem could

be solved, the debris is removed by means of periodic short manual lifting of the spectrometer pontoon. Additionally, a steel baffle was installed downstream of the pontoon. The baffle dams the water for a few centimetres – which allowed a higher installation position of the pontoon. This measure also contributed towards a more stable operation during low flow periods during night hours – when the water level is just a few centimetres. A sampling hose is installed at the stern of the pontoon; with this equity between samples for the in-line measurement and laboratory analysis shall be achieved.

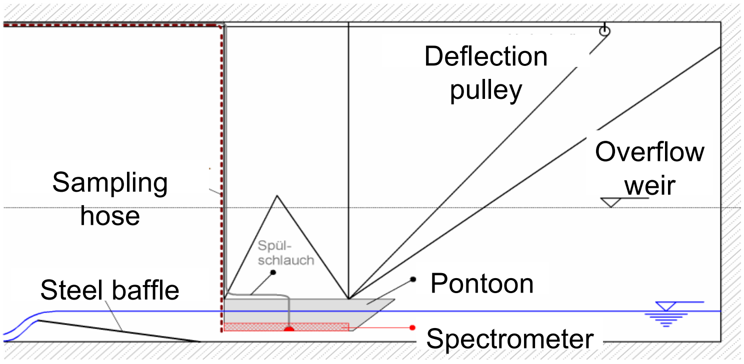


Figure 1: Installation of a submersible spectrometer in a pontoon for continuous measurements in a CSO-chamber

Figure 2 shows the position of the spectrometer pontoon during different flow conditions.

Figure 2: Floating pontoon with spectrometer under varying flow consitions. Left: Dry weather flow, Middle: CSO overflow, Right: Extremely high flow

Figure 3 shows the installation of an ISE-ammonium probe in an open sewer channel closely upstream of a wastewater treatment plant during a research study in Switzerland. The installation allowed continuous measurements over a period of two months with no maintenance demand. The monitoring campaign fulfilled its goal of a qualitative assessment of the nitrogen load dynamics.

Figure 3: Installation of an ISE-ammonium probe in an open sewer channel

The concept of the river monitoring station was to setup a compact station with minimum auxiliary equipment. Therefore all probes were adapted for submersed operation. This was necessary due to considerable variations of the water level over the course of the year, which were in the range of 7.5 m. In August 2002 heavy floods occurred while in summer 2003 the water level decreased to an extent that the sensors fell dry. Figure 4 shows the river monitoring station at different water levels.

Figure 4: Compact water quality monitoring station at the Danube near Vienna. Left: Water level too low (probes dry). Right: Submersion depth approx. 1 m

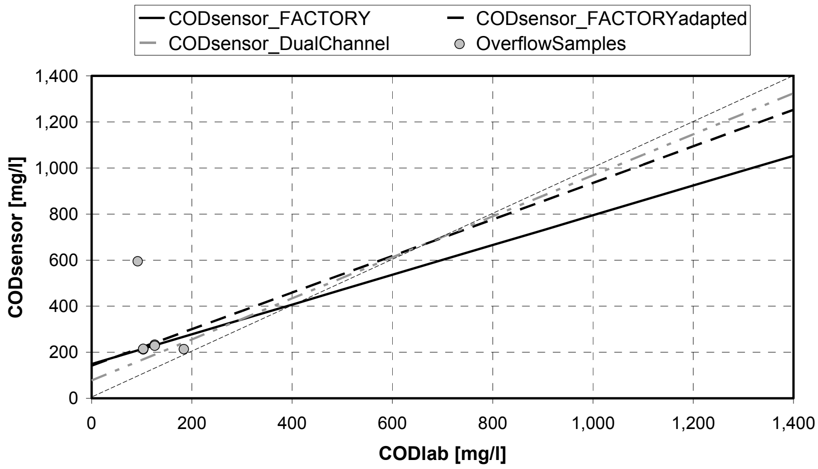
RESULTS AND DISCUSSION

Monitoring in raw wastewater and sewer networks

ISE-sensors are one of the few technologies which allow continuous measurements of ammonium and nitrate in raw wastewater with an acceptable maintenance demand. Due to the measurement principle disturbances the variation of concentration of disturbance ions has to be considered; in raw wastewater the measurement error due to disturbances ions usually is less than 5 % (Winkler et al., 2004).
For measurements in sewer networks the variation of the NH_4-N:N_{total}-ratio has to be considered. Depending on a large number of factors this ratio can vary significantly; the ISE-sensor measures ammonium only while for the receiving water body the N_{total}-load is the important factor. Thus, parallel sampling (with an automatic sampler) and subsequent laboratory analysis is required in order to estimate the bandwidth of the NH_4-N:N_{total}-ratio under the different flow conditions at the measurement location. Nevertheless, with ISE-sensors a continuous recording of the NH_4-N-concentration in raw wastewater can be achieved comparably easy – especially in case an in-situ dip-in installation is possible. For example, Thomann et al. (2002) found a standard deviation of the measurement error of 0.62 mg_{NH4-N}/l at an average measurement value of 19.1 mg_{NH4-N}/l during a field test in primary clarifier effluent.
At the sewer monitoring station in Graz a dip-in installation was not possible since the ISE-sensors were not EX-certified. An approach with flow-through cells in a measurement container was chosen, which did not fulfil the expectations. One reason was the small pipe diameter of the flow through cells (3/8”) which caused clogging. A second reason was that the sampling line could not be operated during low flow periods (night hours), since the optimum installation point of the suction hose on the CSO-chamber was found to be in a position 40 cm above the channel invert. Subsequently the ISE-sensors were not continuously exposed to wastewater which has a negative impact on the adaptation of the sensor membrane to the wastewater matrix and subsequently results in a signal drift.

The application of UV-(VIS)-spectroscopy in water quality monitoring is now practised for decades, in recent years more often in-situ applications can be observed. Matsché and Ruider (1982) were among the first to use laboratory UV-measurements at a wavelength of 260 nm for the determination of the COD-concentration in WWTP effluent. Later first in-situ sensors were developed (WIM 156, 1999) which used a single wavelength (254 nm) or two wavelengths (254 nm and 436 nm); the second wavelength (436 nm) is used for turbidity compensation. Other single or dual-wavelength sensors were developed for nitrate measurement. Early as well as later investigations clearly showed, that often a good correlation between UV-absorption and the concentration of organic compounds or nitrate can be found, but the correlation function is always application specific.

Also the measurements at the sewer monitoring station in Graz confirmed these results. In the beginning the spectrometer was operated with a factory calibration, which only gives a rough correlation between the measured absorption and the parameter of interest (COD, BOD, TOC, NO_3-N). Later the factory calibration was adapted by means of a series of reference measurements. This improved the coefficient of variation and the 95%-confidence interval; in the lower concentration range still substantial differences between the laboratory and the in-line measurements remained (Figure 5). Unfortunately, during stormflow events – due to dilution effects – the occurring concentrations are in this low range and subsequently the estimated discharge loads have only limited accuracy (Gruber et al., 2004).



FACTORY=factory calibration; FACTORYadapted=linear regression of factory calibration based on reference measurements; DualChannel= linear regression function (Abs(254 nm)-Abs(436 nm))

Figure 5: Correlation function for COD_{total} between laboratory measurements and equivalent values derived from an in-situ UV-VIS-measurement in a CSO-overflow chamber.

In Figure 5 the grey circles show the correlation between the laboratory and sensor values (using the FACTORYadapted calibration) for a few samples from CSO-overflow events. One of these samples is an outlier likely caused by partly obstruction of the optical path by large particles (Figure 6). Two of the samples can hardly be seen in Figure 5, since these samples almost overlap.

It clearly can be seen that the relative error of the samples from the overflow events is significant; on the other hand a larger number of overflow samples (assuming a similar fingerprint) would not have changed the calibration function significantly, since four out of the six samples lay almost on the correlation function for the "FACTORYadapted"-calibration function.

In the following Table 2 some key figures for the different calibrations are summarized:

Table 2: Key figures of different calibration functions of Figure 5

	FACTORY	FACTORYadapted	DualChannel
Coefficient of variation	0.92	0.92	0.89
95% confidence interval; relative to mean lab value	364	200	213
Mean lab value	708	708	708

River water quality monitoring

The river water quality monitoring station was installed in the river Danube downstream of the main Vienna WWTP. An extension of this plant is currently under construction (Müller-Rechberger et al., 2002); operation of the extended plant is due to start in 2005.

The location of the river quality monitoring station allows continuous monitoring of the impact of the plant discharge on the water quality. Of special interest is the comparison of the current situation with the situation after completion of the plant extension. The data from the monitoring station will allow a detailed evaluation of the effectiveness of the plant improvement measures.

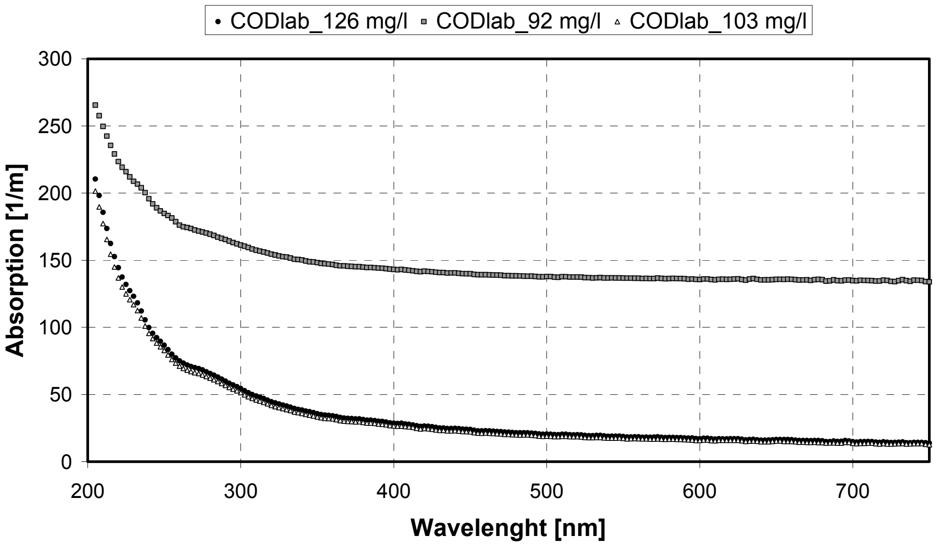


Figure 6: Fingerprints of different samples during overflow events

Figure 7 shows ammonium and nitrate measurement results from the river monitoring station for a period of one week. The ammonium measurement shows a periodic pattern with two daily maxima stemming from the WWTP discharge plume; the WWTP effluent and the monitoring station are located on the South river bank. The nitrate measurement shows corresponding peaks to the measured ammonium peak concentrations. Nitrate was measured with an ion-sensitive sensor (ISE) and an UV-VIS spectrometer; the two measurement methods yield similar results. The results show that the ISE-sensors can be operated also in the low concentration range in case the water matrix is long term stable, which is the case in river water. The lower detection limit of the ISE-sensors ($NH4^+$, $NO3^-$) is in the range of 0.1 mg_N/l. The noise in the nitrate-ISE-signal is due to malfunctions of the data logging system.

The ISE-sensors were calibrated by means of a two-point calibration with standard addition on a river water sample. The UV-VIS spectrometer was calibrated with reference measurements using a nitrate cuvette test (LANGE LCK 339).

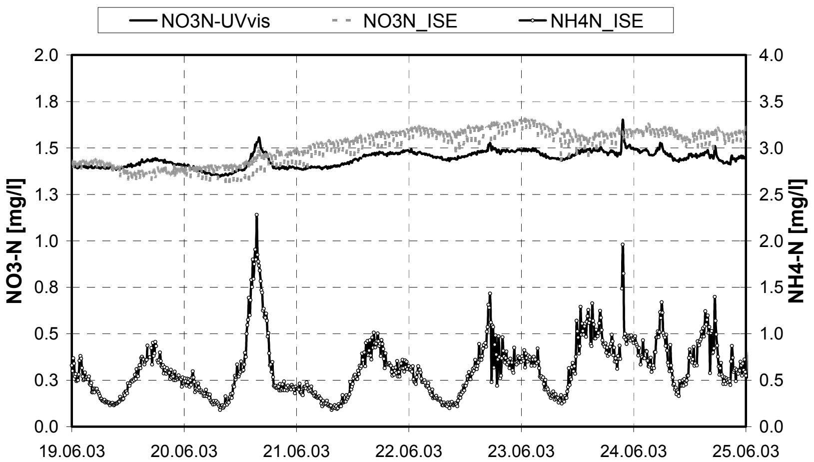


Figure 7: Ammonium and nitrate concentrations in the Danube river downstream the main Vienna WWTP. ISE=Ion-sensitive sensor; UVvis=UV-VIS-spectrometer

CONCLUSIONS

Good quality dynamic data is an essential prerequisite for modelling and optimisation of dynamic systems such as urban water management systems; optimization in the sense of minimizing the total emitted pollution loads is only possible in case transient events can be studied in detail.

Classic monitoring campaigns using automated sampling and subsequent laboratory analysis yield only limited dynamic information and are labour and cost intensive. In opposite, continuous measurements are capable to deliver dynamic data over long periods. Today, an increasing number of in-situ sensor systems become available which allows long-term monitoring even in raw wastewater or sewer networks with acceptable maintenance demand. Sufficient measures have to be taken to ensure the data quality of the continuous measurements, in some cases only a limited accuracy will be achievable. Overall the value of continuous long term recordings with maybe limited accuracy have to put in perspective with results from short term observations with probably higher accuracy.

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