Management of sensible water uses with the help of innovative sensor technology - Part 1: Background and project aims

N. Fleischmann*, M. Werderitsch** and H. Weyermayr [+]

* Department for Sanitary Engineering and Water Pollution Control (IWGA -SIG)
University of Agricultural Sciences Vienna (BOKU), Muthgasse 18, A-1190 Vienna, Austria.
Email: fleischmann@iwga-sig.boku.ac.at
** Vienna Waterworks, Grabnergasse 4-6, A-1160 Vienna, Austria. Email: wma@m31.magwien.gv.at
[+] Errichtungsgesellschaft Marchfeldkanal, Franz Mair-Straße 47, A-2232 Deutsch Wagram, Austria.
Email: harald.weyermayr@marchfeldkanal.at

Abstract
An entirely sensor based control and early warning network has been applied for two surface water uses in the EU-LIFE project "Management of sensible water uses with the help of innovative sensor technology" (contract No. LIFE 99 ENV/A/000403). In both pilot applications it is important to react in real time to water quality changes of the river Danube. The application development in practice revealed that apart from instrumentation itself a number of other modules are necessary before a measurement system provides the desired information to the plant operator. The objective of water quality measurement is information and analogue to information theory the monitoring system has to adopt the pragmatic, syntactic and semantic signal functions. It is emphasised that sensor based water quality information systems require tailor-made quality control schemes, including recalibration and validation, online data evaluation in order to present information rather than data. The design considerations and the operational concepts of the early warning network are discussed in this paper, part 2 (Fleischmann et al., 2002) shows the results.

Keywords
Early warning, control system, sensor, bankside filtration, groundwater recharge, spectrometry

INTRODUCTION

A considerable number of water management and process control issues is concerned with dynamic changes of water quality parameters. The reason for these water quality changes are on one the hand natural fluctuations (see Figure 1) as a inherent characteristic of aquatic systems and on the other hand anthropogenic influences on these aquatic systems.

Nowadays water users and water quality management in general have to deal in one or another way with this dynamic behaviour. In the past the predominant approach was to neglect the dynamic nature and to use stationary representations of the system under consideration. The time scales of investigation were selected in a way that the dynamic behaviour was only of minor importance. This approximation has several drawbacks and hampers optimal water quality management or optimal process control.

Stationary approaches to dynamic systems are a simplification but they had to be selected because appropriate tools to deal with this phenomenon have simply not been available.

The last years have seen an increasing use and acceptance of dynamic mathematical process models, which are one tool to deal with time variant behaviour. This development was enabled through the availability of powerful computers and through intensive research for model development. Still it was difficult to produce input data and to validate the results of these models, as the necessary measurements based on experiments and laboratory analysis have been very costly. In other words an affordable measurement technology to trace dynamic water quality changes is sort of a missing link between reality and model.

With the considerable progress in sensor technology, electrooptic, semiconductor technology an ever increasing set of water quality parameters can be measured reliably online and in-situ. But there are little experiences with the performance of sensor based water quality information systems in practise. The convenience of such systems for a certain water quality problem/issue has to be evaluated on a case to case basis. It is the intention of this project to demonstrate, test and validate such a system for two „sensible“ water uses.

PROJECT AREA

The first application of the system is a drinking water abstraction in a bankside filtration plant and the second a groundwater recharge plant. Both systems use naturally soil filtered surface (river) water and thus depend absolutely on the highly dynamic surface water quality of the Danube.

It was the hypothesis of this project that a network of online in-situ measurement stations will help to gain insight in the complex interactions between river water (quality / quantity) and the adjacent groundwater bodies. The plant operators are searching for new management and control options for their water uses, whereupon the reduction of contamination risks came to the fore.

Little less than 50% of Europes drinking water supply is based somehow on surface water. The concept to measure important water quality parameters online and in-situ is not only a possibility to improve drinking water quality and to reduce contamination risk and but also a possibility to identify and quantify natural and anthropogenic influences on surface water quality. This information is of considerable importance for the optimal allocation of resources to the various activities of water quality management.

With the second application the project helps to protect groundwater resources, because river water of insufficient quality will not be used for recharge. The risk of failure of the filtration zone can be reduced, because only water of convenient quality will be used for remediation.

Vienna Water Supply

The city of Vienna Waterworks supplies drinking water for some 1,5 million inhabitants. The daily average demand of drinking water is 400,000 m³, which is mainly covered by the two spring water mains (Figure 2) – each accounts for about 50 % of the demand. In order to increase the supply security a number of new water sources has been made available recently. The objective is to cover about the capacity of on of the spring water mains by sources other than carstic springs. The cornerstone of this concept are the 3rd Viennese Water pipeline - Moosbrunn waterwork, the water sources in Vienna (waterworks Lobau and Nussdorf) and the new Danube island well field (Figure 2). The danube island well field consists of 8 bankside filtration wells, it is a new type of water source for the Viennese waterworks. Consequently a new monitoring and operation concept had to be developed. This project is part of this new monitoring concept and deals especially with real time water quality measurement for early warning and plant control.

The Vienna waterworks have considerable experience with early warning systems as the water characteristics of the karstic spring water is varying as a result of the varying retention times in the karstic massifs. Tourism and mountain pasture at the top of the kastic massifs in areas of the catchments has a certain influence to the spring water regarding microbiological parameters.

The existing early warning system for the carstic springs consist of 14 stations. Parameters like pH, temperature, oxygen content, DOC (Dissolved organic carbon), turbidity and UV-absorbance (254 nm) are measured continuously. Measurement results are transmitted via radio transmission to the control center. The experience over the years of operation has revealed on the one hand that some parameters, although difficult to maintain, deliver redundant or even useless informtion (O2, pH) and on the other hand that certain important water characteristics (e.g. microbiology, regrowth factors) are still not covered in a satisfying way.

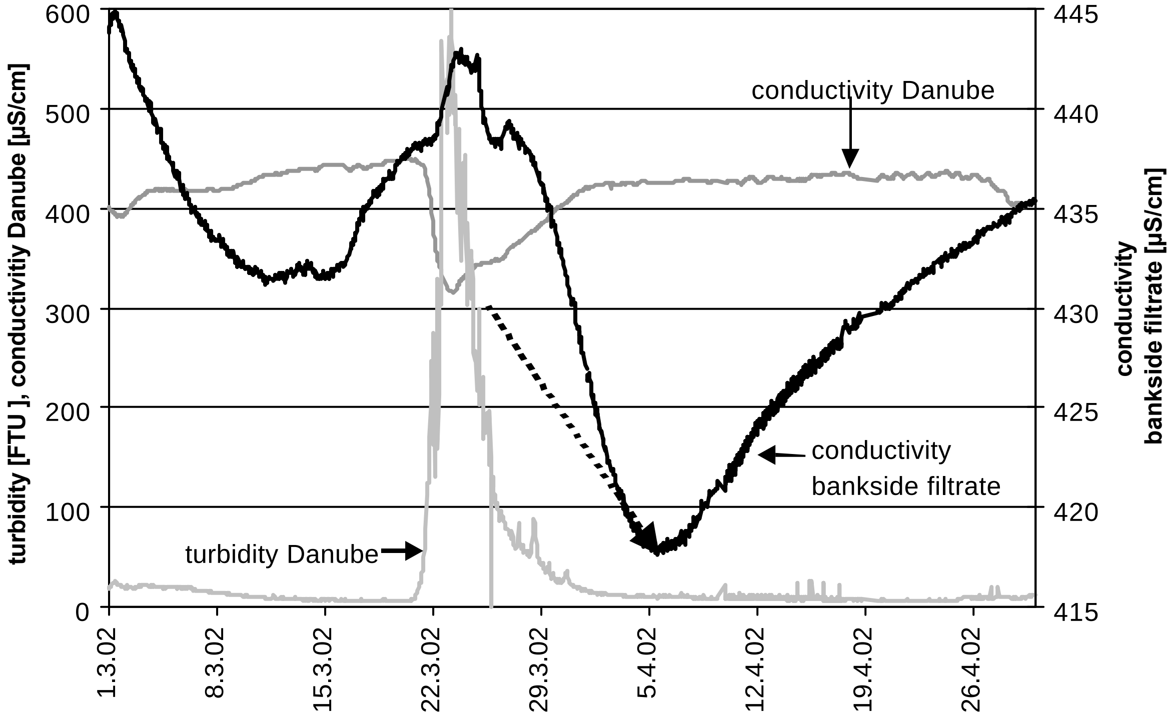

Figure 1: Time series for a 2 month period of the turbidity and conductivity of the Danube and of conductivity in the adjacent groundwater (bankside filtrate) after heavy precipitation in the catchment. The graph illustrates the highly dynamic nature of the Danube (a 60fold increase within 1.5 days) and the interaction with the groundwater (indicated by the dotted arrow). The different shapes of the turbidity and the salinity curves show the different behaviour of (dissolved) ions and suspended matter.

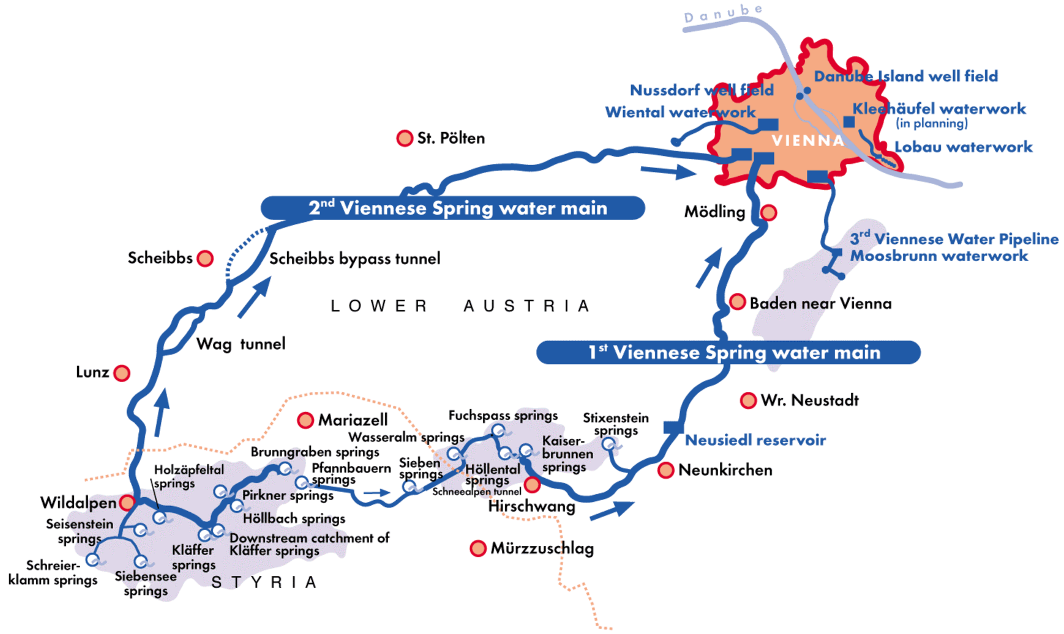

Figure 2: Water sources used for the drinking water supply of Vienna.

Based on the results of the existing early warning system, control actions can be taken in case of unfavourable spring water quality. Discharging the spring water or increased dosing of disinfectant are two successful and simple strategies. For both of them suitable indicators as control parameters are necessary. At the moment UV-absorbance (254 nm) and turbidity are used as control parameters. UV-absorbance (254 nm) is superior to turbidity as indicator of microbiological influences. Studies were carried out aiming at better control parameters (e.g. particle counter). One of the substantial interests of the Vienna Waterworks in this LIFE – project was to improve the control scheme by developing new control parameters.

Bankside filtration. In order to maintain the high quality standards a similarily effective early warning and control system is desired for the new bankside filtration faciltiy. But this facility is confronted with considerably different conditions as compared to the existing carstic and groundwater sources.

For the carstic springs the main reasons for unfavourable raw water quality are heavy precipitation and extraordinary snowmelt whereas for the bankside filtration facilty both natural and anthropogenic transient pollution events have to be considered. Toxic peak loads caused by accidents, refractory organic carbon, micropollutants are by far more relevant for the bankside wells and had not to be regarded for the carstic springs. Therefore it was necessary to apply new technologies.

The wells are located in the urban area of Vienna, on an artificial island in the Danube. The local situation is displayed in Figure 3 and Figure 4. Previous studies revealed various possible sources of sudden contamination, amongst shipping, railway and road traffic acrross the river as well as industry along the Danube.

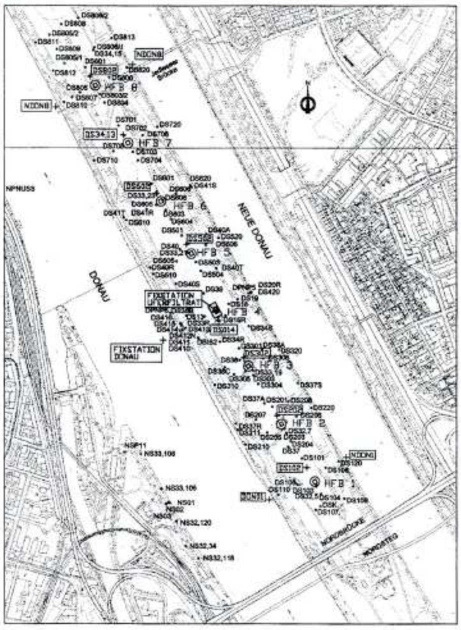

Figure 3: Wells and boreholes at the Danube island.

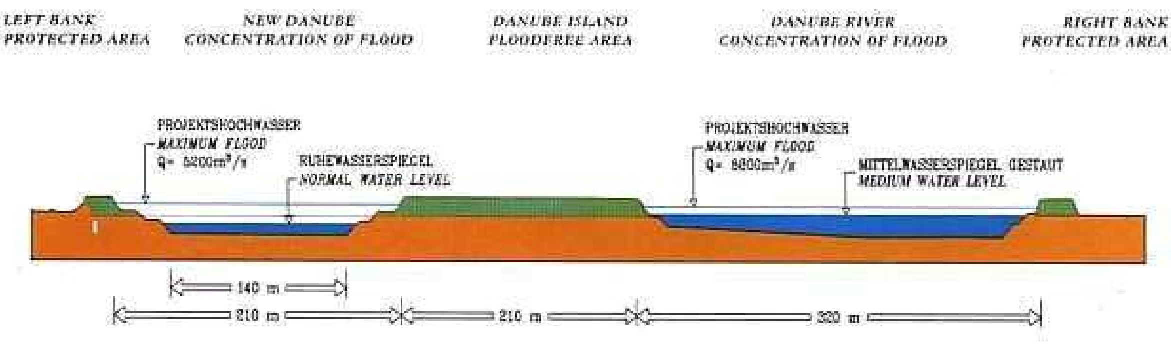

Figure 4: cross section of the Danube. On the right side the river on the left side the stormwater channel ("new Danube"). The drinking water wells are located on the island in the middle. Water level differences of several meters lead to a constant flow from the Danube through the island to the channel.

Groundwater Recharge Plant

Several recharge plants have been built for the restoration of an overexploited aquifer near Vienna. The main treatment step is slow sand filtration. A 15 km channel (Marchfeldkanal) supplies Danube water for groundwater recharge as well as for irrigation purposes. A similar early warning concept has been established because the conditions and the risks are very similar to the bankside filtration nearby.

The alarm system distinguishes two levels of reaction

- Closing the water abstraction (prevents Danube water of unfavourable quality to enter the channel)
- Closing the inlet of the recharge plant (prevents disturbances of the recharge plant itself and pollutant transfer to the groundwater)

Apart from protection against hazardous substances it is important to avoid excessive transfer of suspended matter into the channel. Subsequent sedimentation would not only lead to high and undesired oxygen demands at the water – riverbed interface but also to changes of the hydraulic capacity of the channel.

THE MONITORING SYSTEM

The monitoring system consists of the station hardware, the data evaluation procedures and of the data transfer infrastructure. On site installations include four monitoring stations, 2 continuously monitored testfilters and systems of continuous sampling for a total of 9 measurement points.

One principle of the monitoring station design was to rely entirely on sensor measurements (in-situ real-time, directly in the process). The on-line measurements are accompanied by conventional sampling and laboratory analysis for purposes of calibration and quality control. Laboratory parameters include TOC, DOC, Nitrate, Chloride, SO_4, PO_4, SAC 254 and occasionally various micropollutants.

The concept of sensor measurements has the following limitations:

- Trueness: Sensor measurements can deviate in different ways (drift, shift, offset) from the true value. Operation of a sensor system has to go along with a quality control concept in order to trace the deviations and to avoid misleading information. Such a system that detects drift-, shift- and outlier effects as well as unsatisfactory calibration curves has been proposed by Thomann (2001). The approach is based on the analysis of comparative measurements between the sensor and a reference method.
- Selectivity: The number of parameters that can be measured with sensors directly in the water is limited but it can be expected that more sophisticated sensors will soon be available. Especially biosensors and sensors based on polarographic principles as well as devices with increased selectivity through polymer coatings and electrooptic detection principles are promising strategies.

In spite of these limitations a sensor based system can produce meaningful water quality information, if the monitoring strategy takes the weaknesses in account.

- The basic requirement is the quality control system. It has the task to give a realistic picture of instrument performance in terms of chemometric descriptors like trueness, precision, selectivity, limit of detection, range, cross sensitivities etc. and it has to define possible causes and consequences in case of unsatisfactory results. The first action for the establishment of a Quality control system is the assessment of appropriate reference methods.
- Most sensors need to be calibrated for the water matrix of concern and calibrations are merely transferable from one location to another. The sensor performance depends on the quality of the calibration procedures e.g whether interfering factors are taken into account or not. In a simple case this might be the temperature and atmospheric pressure for an oxygen measurement. In

other cases a number of cross sensitivities and matrix effects will require more complicated procedures of multivariate calibration. The concept of local multiparameter calibration for is one of the cornerstones of the monitoring network.

- Offset changes are very common for sensors. In some cases it is not necessary to know the absolute value of a measurement but the differences between two locations or over time. If only one sensor is used for the measurement, offset changes will not impose any restrictions to the system. E.g. the elimination efficiency of the bankside filtration can be assessed by the difference between the results in the river and in the well. As far as differences between several locations are concerned it is necessary to take the transport processes between those locations into account. Respiration experiments are an example for the evaluation of difference over time.
- Multiparameter measurement: Selectivity can be increased by the simultaneous measurement of different parameters. This approach is based on sensor arrays and multivariate data evaluation and has been successfully applied for quantitative as well as for qualitative air quality measurements ("electronic nose"). Several measurement principles deliver a two- or three-dimensional signal which contains information about a number of parameters. Absorption spectrometry is one of these principles and has been applied in this project.

Multiparameter spectrometric sensor

The sensor measures either absorption from 200 nm to 750 nm with a spectral resolution of 2nm or only ultraviolet light (200-400 nm) with as spectral resolution of less than 1 nm. Instrument stability is guaranteed by a 2-beam construction of the transfer optics. The measurement beam passes through the liquid, where the light is absorbed by dissolved substances and scattered by particulate matter. The absorption spectrum is detected on a diode array and further processed in the on-board microprocessor. The resulting spectra can be evaluated with a tailor-made spectrometric measurement and calibration software.

In absorption spectrometry the loss of radiant energy at different wavelengths (the spectrum) is evaluated in order to derive quantitative or qualitative information on substances or substance groups. Single substances show a certain spectrum, the overall spectrum of a sample is the sum of all single substance absorptions at any measured wavelength. Spectrometric measurement methods for the following single substances or surrogate parameters have been used within the project:

- Nitrate
- Nitrite
- Benzene
- Nitrobenzene
- Chloroform
- SAC
- turbidity / suspended solids
- TOCeq

The sensor is built as a compact probe (44 x 580 mm), capable of measuring optical spectra directly in the boreholes or in the process. Sensitivity of absorption measurement depends among others upon the optical path length. The path length of the sensor can be adjusted, for river water 35 mm and for drinking water 100mm path length have been installed. The instrument is equipped with an auto-cleaning system. On-board electronics control the entire measurement procedure.

One basic requirement for a monitoring system is long term stability. In general long term stability can be hampered by instrument drift, by sensor fouling or by matrix changes. Instrument stability is guaranteed by the double beam principle. A major problem with any type of immersed sensor is biofouling. Bacterial growth or other depositions on the instrument water interface can lead to undesirable changes of the signal. As there is no general model to predict the influence of biofilms it has to be assessed for every local installation. Figure 5 shows the measurement path of a spectrometric probe after 3 month operation without maintenance. Although all metallic surfaces are covered with depositions this is not the case for the lens. Nevertheless at some other measurement locations it was unavoidable to use the auto-cleaning system.

Figure 5: Depositions on the sensor surfaces can lead to deterioration of the sensor signals. Poor long-term stability or high maintenance cost are the consequence. In this case the optical interface has not been affected by the depositions.

Local multiparameter calibration

A crucial feature for sensors is their performance with untreated samples. Calibration results with pure substances and under laboratory conditions are necessary and a first step but their results are not transferable to the field application. Natural waters, characterised by a matrix of numerous substances, cause cross sensitivities, environmental conditions (temperature changes, humidity, ...) may influence the instrument signals. Therefore the performance in-situ is inferior to the performance under controlled conditions. Apart from instrumental accuracy, detection limits and measurement ranges depend before all on the variability of the background matrix.

The procedure that has been chosen in order to overcome these limitation is a local calibration for the parameters of concern. Local calibration is based on in-situ measurements and parallel laboratory analysis with reference methods. Previous feasibility studies have shown that local calibration improves the performance (selectivity, trueness and precision) for quantitative measurements. Hence, a good calibration function is an essential part of in-situ measurement methods. Rules that are a precondition for successful local calibrations are given at Langergraber et al. (2002).

Testfilters

The monitoring network includes testfilters as a reference system. In this case study 2 parallel fixed bed filter columns with a depth of 9 m each where used.

Testfilters are a model environment and have the task to reproduce the biological degradation processes during riverbank filtration (Gimbel and Mälzer, 1987). The underground passage from the river to the well can be regarded as the first step of drinking water treatment. More than 90 % of the degradation takes place within the first meters of the underground passage. With the help of testfilters, statements about substances expected to pass the bank filtration can be made before they appear in the drinking water well at the end of the riverbank filtration.

The specific novelty in this project is that information about testfilter performance should be collected from on-line measurements only. After an initial calibration phase with the help of laboratory parameters, everyday operation includes on-line measurements and periodic re-calibrations only. Detection limits and selectivity of field instrumentation cannot be compared with laboratory trace analysis. Nevertheless for some specific monitoring tasks other considerations like measurement frequency can lead to a superior performance of sensor systems.

Data Evaluation and Data Transfer

For early warning systems it is necessary to combine automatic measurement with automatic data evaluation and data transfer. In this measurement network the following elements have been realised:

- plausibility control and signal conditioning,
- data storage and visualisation,
- calibration,
- remote control,
- automatic data transfer to a central database, and
- public web interface for data visualisation.

Every station is controlled by a custom software, based on the development tool LabView®. The database and the web interface have been realised under LINUX. Plausibility control includes limits for the measurement range, automatic detection of stable/unstable sensor signals in terms of standard deviation and trend. Signal conditioning includes digital filters based on sector-wise and boxcar averaging as well as on polynomial smoothing. Data storage concerns raw and reduced data as well as status reports and user activities. In-situ visualisation displays time series with free selection of parameter, loction and time scale.

The web interface is based on the idea of maintenance on demand, it can be regarded as an artificial control centre. The responsible person can assess the proper operation of the system from everywhere and at any desired time. Graphic inspection of the results is done by selecting the parameter, the measurement site and the time scale. In case of irregularities on site it is possible to remotely control the system, to change settings or to check the raw data. Just in case that the problems cannot be settled that way somebody has to visit the measurement station. The desired effect is to reduce maintenance cost due to regular travels to the measurement sites, but without inducing drawbacks on the reliability of the system.

CONCLUSIONS

Within the EU-LIFE99 project ENV/A/000403 "Management of sensible water uses with the help of innovative sensor technology" an early warning system was developed for the protection of bankside wells and a groundwater recharge plant. The monitoring network design is based on sensor measurements only. The system indicates that using intelligent data combination, interpretation and visualisation much better information on water quality can be produced by measuring few parameters on-line (e.g. UV/VIS spectra and O_2-consumption due to biological effects) in comparison to grab sampling and laboratory analysis.

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