Real-time on-line monitoring of contaminants in water

Developing a research strategy from utility experiences and needs.
Real-time on-line monitoring of contaminants in water

Developing a research strategy from utility experiences and needs.
Colophon

Title
Real-time on-line monitoring of contaminants in water

Developing a research strategy from utility experiences and needs.

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Project manager
Annemarie van Wezel

Client
UKWIR/Awwa Research Foundation/BTO

Quality Assurance
Theo van den Hoven, Ariadne Hogenboom, Gertjan Medema, Annemarie van Wezel

Authors
Bram van der Gaag, Jurgen Volz

Sent to
UKWIR/ Awwa Research Foundation /BTO-participants
Preface

The project “Real-time On-line Monitoring of Contaminants in Water” is a collaborative effort of UKWIR, Awwa Research Foundation (AwwaRF) and Kiwa Water Research. The latter organisation is contributing within the framework of BTO, which is the joint research programme of the Dutch and Belgium (Dutch-speaking regions) water works.

Current and emerging sensor technologies and utility experiences with on-line monitoring using those technologies were reviewed at an International workshop. Knowledge gaps were identified and a research agenda developed. A unique mix of end users, manufacturers, vendors and research organisations was involved in the workshop. This report gives a synopsis of the findings of the workshop.

The project team acknowledges the valuable contribution of workshop representatives. In particular we want to thank Mike Farrimond (UKWIR), David Holt (UKWIR) and Hsiao-Wen Chen (AwwaRF) for convening the workshops with utilities in the UK and US, and Frans Schulting (GWRC) for facilitating the research strategy workshop including the linkages to other GWRC-members. Also we acknowledge the contribution of the members of the AwwaRF project advisory committee.
Summary

This report describes current and emerging sensor technologies for real-time and on-line monitoring of contaminants, makes an inventory of water utility experiences and needs and presents a research agenda. Information was gathered from workshops with utility representatives in the UK, US and the Netherlands, from additional data provided by members of the Global Water Research Coalition, and from a technology review of current sensor systems.

Water utilities experiences
Sensors and on-line monitoring systems may have clear and multiple benefits for water utilities. Possible applications are in intake protection, control of operations, security, and providing information to customers. Currently, on-line sensors are frequently deployed for monitoring physical parameters such as flow rate, turbidity, pH and water temperature. Sensors are also used for monitoring chemical and biological parameters such as free chlorine, fluoride, spectral adsorption and biomonitor responses.

Although sensors are increasingly appearing on the market, effective implementation in water utilities has not been realized particularly for those sensors based on chemical or biochemical detection processes. There have been several reasons suggested for the lack of implementation:
• sensors do not meet practical utility needs
• poor links between available sensor technologies and water quality regulations
• verification schemes do not sufficiently match utility practices
• challenge of managing large data quantities and translating them into meaningful information for operational processes.

Available technologies
Reliable, robust and well-established equipment is available for (Table 0-1):
• physical measurements (redox potential, flow, pressure, temperature, conductivity, pH and turbidity).
• some chemical reaction derived monitors such as iron, manganese, aluminium, nitrate and chlorine.
• HPLC UV, GC-MS for a limited number of organic pollutants.
• Some biomonitors such as those based on algae and Daphnia responses.

Less reliable performance is reported for equipment for spectral analysis, oxygen, chlorophyll a, particle counts, ammonia and oil in water.

Parameters for which companies expressed interest in having more reliable monitoring equipment include low-level organics, pesticides, hydrocarbons, bromates, ozone, total nitrogen, UV 254, nitrate, DOC, THMs and bacteria.

Promising developments are:
• Biosensors, which utilise the binding of a target compound with biological agents such as antibodies, enzymes, DNA receptors and cells;
• Physical sensors with the capability of detecting chemical pollutants on the basis of their physical properties. In particular developments are promising for optical sensors;
• Multi-sensor platforms, which combine different conventional (currently mostly physical) sensors with technologies for data handling and remote reading and control.

On-line sensors for (pathogenic) micro-organisms remain a major technological challenge for water quality applications.

Table 0-1: Summary of the state of application of on-line monitoring equipment.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Parameters</th>
<th>Surface water resource</th>
<th>Ground water resource</th>
<th>Treatment works</th>
<th>Finished water</th>
<th>Distribution network</th>
<th>Type of monitoring</th>
</tr>
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<tr>
<td>Thermometer</td>
<td>Temperature</td>
<td></td>
<td></td>
<td></td>
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<td>Trend</td>
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<tr>
<td>Oxygen probe</td>
<td>Dissolved oxygen</td>
<td></td>
<td></td>
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<td></td>
<td>Trend</td>
</tr>
<tr>
<td>pH-meter</td>
<td>pH</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>Trend</td>
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<tr>
<td>Turbidity meter</td>
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<td></td>
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<td></td>
<td></td>
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<td>Trend Alarm</td>
</tr>
<tr>
<td>Conductivity cell</td>
<td>Conductivity</td>
<td></td>
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<td></td>
<td></td>
<td>Trend</td>
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<tr>
<td>Ion-selective electrodes</td>
<td>Ions</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>Trend</td>
</tr>
<tr>
<td>Chemical reaction derived monitors</td>
<td>Iron, manganese, aluminium, nitrate and chlorine.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Trend</td>
</tr>
<tr>
<td>Particle counter</td>
<td>Particles</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Algae monitor</td>
<td>Herbicides</td>
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<tr>
<td>Daphnia-monitor</td>
<td>Pesticides (insecticides/ cholinesterase inhibitors)</td>
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<td>Alarm</td>
</tr>
<tr>
<td>Mussel monitor</td>
<td>Organohalogenated-compounds, Anti-fouling agents (TBT)</td>
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<td></td>
<td>Alarm</td>
</tr>
<tr>
<td>Bacteria monitor</td>
<td>Benzene, chlorinated benzenes, pesticides, halogenated hydrocarbons</td>
<td></td>
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<td></td>
<td>Alarm</td>
</tr>
<tr>
<td>Fish monitor</td>
<td>Broad spectrum of chemical pollutants</td>
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<tr>
<td>UV-probe</td>
<td>FTU/NTU, TSS, UV-254/SAC, COD, TOC, BOD, AOC, NO3, NO2, NH4, Hydrogen Sulfide, BTX, O2, Ozone</td>
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<tr>
<td>GC-MS</td>
<td>Broad spectrum of chemical pollutants</td>
<td></td>
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<tr>
<td>LC-UV (DAD)</td>
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<tr>
<td>LC-MS</td>
<td>Broad spectrum of chemical pollutants</td>
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<td>Trend Alarm</td>
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<tr>
<td>Radio activity</td>
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<td></td>
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<td></td>
<td>Alarm</td>
</tr>
</tbody>
</table>

• green (grey in black-and-white print): reliable, robust and well-established for research and (most of these) also for routine monitoring application. Some equipment such as the chemical reaction based equipment and the biomonitors require intensive maintenance.
• yellow (light grey in black-and-white print): under development.
Research agenda
The research agenda was developed during the Workshop held at Kiwa Water Research. This provided a forum for key stakeholders to discuss needs and experiences. All participants agreed that more extensive cooperation between manufacturers, researchers and water utilities is required for stimulating innovation in the development of monitoring equipment and shortening the time to implementation. A recent European multi-stakeholder project (TECHNEAU) demonstrates the power of this type of cooperation.

Workshop participants developed the following five areas for future research and activities:

• monitoring equipment should better fit practical utility needs;
• verification schemes should sufficiently match utility practices;
• available sensor technologies should link to water quality regulations;
• technologies and practices should be developed to manage the large quantities of data and translate these into information for operational processes;
• exchange of information and experience with the use of sensors between water utilities, manufacturers and pilot researchers.

From the above themes, the following five areas for future research and activities have been identified:

• More in-depth review of current on-line monitoring practices to meet utility needs. Although this project has taken the first valuable step, the workshop concluded that a more in-depth review on utility drivers and needs for sensors, including a costs-benefits analysis, is needed. More countries should be involved in this in-depth review.
• Consistency of testing. The protocols for testing on-line measurement equipment used by vendors, pilot researchers and water utilities do not match. Workshop participants identified the need for harmonisation in testing protocols in the chain from development to product use. An advantage is a shorter time to market, appreciated by both vendors and water utilities.
• Linking sensor development to water quality regulations. Data produced by on-line monitoring systems provide real-time information on water quality. This differs from the established practice of laboratory analysis which can only confirm that the water is of satisfactory quality, in many cases, after the water has been distributed. On-line, real-time monitoring is an upcoming technology and will have implications on the regulatory framework for assessing water quality.
• Data handling. Reliance on water monitoring and alarm systems have increased due to the greater complexity of treatment processes, increased automation, reduced staffing, and the regulatory and societal drivers to provide higher levels of security and safety. Inevitably, alarms have increased, making it more difficult to respond correctly. The proposed project will examine sensor and (statistical) data handling and analysis tools to transform data into information that can be used as a basis for risk management.
• Establishment of Community of Practice on Sensors in the Water Industry. To exploit the full potential of the sensor technology available (today and in the future), exchange of information and know-how on development and user experience of sensors is of the utmost importance to the water industry. A Community of Practice on sensors is proposed with the task of facilitating information exchange by an annual workshop and a web-based platform.
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<th>Definition</th>
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<td>AOC</td>
<td>Assimilable Organic Carbon</td>
</tr>
<tr>
<td>ATP</td>
<td>Adenosine Triphosphate</td>
</tr>
<tr>
<td>AwwaRF</td>
<td>Awwa Research Foundation</td>
</tr>
<tr>
<td>B</td>
<td>Belgium</td>
</tr>
<tr>
<td>BOD</td>
<td>Biological Oxygen Demand</td>
</tr>
<tr>
<td>BTO</td>
<td>Bedrijfstakonderzoek (Joint Research Program)</td>
</tr>
<tr>
<td>BTX</td>
<td>Benzene, Toluene and Xylene</td>
</tr>
<tr>
<td>Ca</td>
<td>Calcium</td>
</tr>
<tr>
<td>CDC</td>
<td>US Centers for Disease Control and Prevention</td>
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<tr>
<td>CE</td>
<td>Capillary Electrophoresis</td>
</tr>
<tr>
<td>CL</td>
<td>Chlorine</td>
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<tr>
<td>COD</td>
<td>Chemical Oxygen Demand</td>
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<tr>
<td>CWS</td>
<td>Contaminant Warning System</td>
</tr>
<tr>
<td>DAD</td>
<td>Diode Array Detector</td>
</tr>
<tr>
<td>DNA</td>
<td>Deoxyribonucleic acid</td>
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<td>DOC</td>
<td>Dissolved Organic Carbon</td>
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<tr>
<td>DS</td>
<td>Distribution Water</td>
</tr>
<tr>
<td>DSS</td>
<td>Distribution System Simulation</td>
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<td>EMPACT</td>
<td>Environmental Monitoring for Public Access and Community Tracking</td>
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<td>EWS</td>
<td>Early Warning System</td>
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<tr>
<td>FISH</td>
<td>Fluorescence In Situ Hybridization</td>
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<td>FT-IR</td>
<td>Fournier Transform - Infra Red</td>
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<td>FTU</td>
<td>Formazine Turbidity Units</td>
</tr>
<tr>
<td>FW</td>
<td>Water Treatment - Finished Water</td>
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<tr>
<td>GC</td>
<td>Gas Chromatography</td>
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<td>GIS</td>
<td>Global Information System</td>
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<td>GSP</td>
<td>Good Sensor Practice</td>
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<tr>
<td>GW</td>
<td>Ground Water</td>
</tr>
<tr>
<td>GWRC</td>
<td>Global Water Research Coalition</td>
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<tr>
<td>HPLC</td>
<td>High Performance Liquid Chromatography</td>
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<tr>
<td>IEF</td>
<td>Isoelectric Focussing</td>
</tr>
<tr>
<td>ISFET</td>
<td>Ion Selective Field Effect Transistor</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>IR</td>
<td>Infra Red</td>
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<td>IWA</td>
<td>International Water Association</td>
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<td>KWR</td>
<td>Kiwa Water Research</td>
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<tr>
<td>LC</td>
<td>Liquid Chromatography</td>
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<tr>
<td>LOQ</td>
<td>Limit of Quantification</td>
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<td>MALS</td>
<td>Multi-Angle Light Scattering</td>
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<td>Mg</td>
<td>Magnesium</td>
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<tr>
<td>MS</td>
<td>Mass Spectrometry</td>
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<tr>
<td>NASBA</td>
<td>Nucleic Acid Sequence Based Amplification</td>
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<td>NH₄</td>
<td>Ammonium</td>
</tr>
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<td>NHSRC</td>
<td>National Homeland Security Research Center</td>
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<td>Ni</td>
<td>The Netherlands</td>
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<td>NO₂</td>
<td>Nitrite</td>
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<td>NO₃</td>
<td>Nitrate</td>
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<tr>
<td>NSF</td>
<td>NSF-International (historically National Sanitation Foundation)</td>
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<td>NTU</td>
<td>Nephelometric Turbidity Units</td>
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<td>O₂</td>
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<td>PNA</td>
<td>Protein Nucleic Acid</td>
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<td>Quality Assurance</td>
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<td>QTOF</td>
<td>Quadrupole Time-Of-Flight</td>
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<tr>
<td>RW</td>
<td>Stored Raw Water</td>
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<td>SAC</td>
<td>Spectral Absorption Coefficient</td>
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<td>Surface Water</td>
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<td>Tributyltin</td>
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<td>TECHNEAU</td>
<td>Technology Enabled Universal Access to Safe Water</td>
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<td>Total Suspended Solids</td>
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<td>UK</td>
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<td>UKWIR</td>
<td>UK Water Industry Research</td>
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<td>UV</td>
<td>Ultra Violet</td>
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<td>Water Infrastructure Protection Division</td>
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1 Background and objectives

Consumers expect water supply companies to deliver safe drinking water that meets health quality standards, and aesthetic aspects such as colour, turbidity, taste and odour. To this end water supply companies have developed quality management systems and monitoring strategies, using well-established laboratory techniques. New analyses are under development to be proactive regarding emerging contaminants.

In past years there has been a growing interest in the use of on-line monitoring systems, for reasons of:
- lower costs
- response time (laboratory measurements are relatively slow if the results are for treatment processes control or real-time distribution monitoring)
- recent security concerns.

On-line monitoring equipment is installed as early warning systems for water intake, treatment process monitoring and main entry points to the distribution system. Future monitoring systems should be able to distinguish abnormal changes from normal variations.

Several organisations such as Awwa Research Foundation (AwwaRF), the United States Environmental Protection Agency (USEPA) and Kiwa Water Research have reviewed the state of the technological developments of Early Warning Systems (EWS) [Hasan et al. 2005, Oshima et al 2006, van den Broeke et al. 2004, van den Broeke 2005]. A knowledge gap report developed a roadmap for sensor research for wastewater [Treutt et al. 1994, Hill et al 2002]. Furthermore, several reviews have appeared in the open literature [Allan et al. 2006ab, Greenwood et al. 2007, Rodriguez-Mozaz et al. 2006 and 2007].

A central question in the current report is if the recent efforts and developments will meet the water utility needs. The report describes current and emerging sensor technologies, makes an inventory of utility experiences and needs, and presents a research strategy for this area.
2 Methodology

Information was gathered from workshops with utility representatives in the UK, US and the Netherlands, from additional data provided by members of the Global Water Research Coalition, and from a technology review of current sensor systems.

2.1 Inventory of water utility experiences and needs
Water utility experiences and needs were collected by workshops in the UK (September 2006) and US (February 2007) and by interviews in the Netherlands. Prior to the workshops and interviews, utility representatives completed a questionnaire on their experiences with on-line monitoring technologies and the challenges and constraints in the development and application of sensor technology. Questionnaires were also sent to research organisations of the GWRC (see appendix IV for further information).

2.2 Technology review
A description of sensor technologies was prepared from recent publication.

2.3 Research strategy workshop
Both the survey on utility needs and experiences and the technology review were presented and discussed at a research strategy workshop in March 2007 with vendors, utilities and research organisations (see appendix III for the participants). The workshop identified knowledge gaps and developed a future research agenda.
3 Technology review

3.1 Introduction

3.2 Multi-parameter event monitoring technologies
Multi-parameter water quality monitors, or sensor panels, are mainly used in finished water. Typical parameters and techniques used in these monitors are listed in Table 3-1. Single probes or combinations of sensors are commercially available, enabling water utilities to monitor the quality of processed water. Event monitors for intentional contamination in distribution networks use a combination of several parameters for detecting and identifying contaminations [Hach]. There are difficulties with independent validation of this approach as the methods and algorithms employed are company confidential or restricted (non-published information from US Homeland Security and Hach).

Table 3-1: Techniques for multi-parameter monitoring

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorine</td>
<td>• Colorimetric</td>
</tr>
<tr>
<td></td>
<td>• Membrane electrode</td>
</tr>
<tr>
<td>Temperature</td>
<td>• Thermistor</td>
</tr>
<tr>
<td>Dissolved oxygen</td>
<td>• Membrane electrode</td>
</tr>
<tr>
<td></td>
<td>• Optical sensor</td>
</tr>
<tr>
<td>Oxidation-Reduction Potential</td>
<td>• Potentiometric</td>
</tr>
<tr>
<td>pH</td>
<td>• Glass bulb electrode</td>
</tr>
<tr>
<td></td>
<td>• Ion Sensitive Field Effect Transistor (ISFET)</td>
</tr>
<tr>
<td>Turbidity</td>
<td>• Optical sensor</td>
</tr>
<tr>
<td></td>
<td>• Nephelometric</td>
</tr>
<tr>
<td>Conductance</td>
<td>• Conductivity cell</td>
</tr>
<tr>
<td>Ions (Cl-, NO₃⁻, NH₄⁺)</td>
<td>• Ion-selective electrodes</td>
</tr>
</tbody>
</table>

3.3 Sensor technologies for chemical contaminants
Up to 70.000 chemicals are in daily use [Schwarzenbach et al. 2006] and might be present in water resources used for drinking water production. On-line monitors should be able to detect exceedance of quality standards that water utilities are obliged to report. This requires sensitive sensors as standards are often close to the limits of detection, e.g. the EU pesticide standard of 0.1 µg/L.
Another application is detection and monitoring of ‘emerging substances’ for which no specific drinking water quality standards have been set thus far.

3.3.1 Biosensors
This sensor group uses biological components, such as a protein (antibody, enzyme, receptor or DNA), other cell components, cell or whole organisms. Rodriguez-Mozaz et al. [2006] concludes that testing of new biodevices with environmental samples is a must in the final stages of development, but most literature overlooks this stage and only reports applications being tested in either distilled water or buffer solutions. Therefore, for most of the systems reviewed the study of matrix effects, stability issues and comparison with established methods are still crucial steps to be made.

3.3.1.1 Proteins
Protein based biosensors have been developed for a series of chemicals [Proll et al. 2005, Tschmelak et al. 2005 ab]. The sensitivity of protein-based biosensors depends on the physical detection principle used and the affinity of the protein-analyte interaction. Their robustness is influenced by the selectivity of the interaction. Matrix effects can influence the binding between analyte and protein. Since water quality is variable, matrix effects are inevitable and result in a high rate of false positives and negatives [Rodriguez-Mozaz et al. 2006]. Due to the interaction between analyte and reporter molecule, regeneration or replacement of disposable reagents is needed between measurements.

The advantage of affinity based biosensors are the selectivity. In cell-based assays the toxic or genotoxic effect is measured. Proteins of the cell are involved in signal transduction. Compounds first have to bind to these proteins before a signal is initiated. These compound-protein interactions can be visualised with biosensors at µg/L level or even sub-µg/L level. Affinity-based assays are versatile for pre-effect or concentration measurements. Examples of analytes measured with biosensors are: propanil, atrazine, isoproturon, sulphamethizole, bisphenol A, estrone, 17β-estradiol equivalents, nonylphenol, benzene, toluene, xylene, prometryn, trichloroethylene, ametryn, terbuthylazine, simazine, benzenesulfonamide and caffeine.

3.3.1.2 Cells
Cell assays detect toxic effects (e.g. acute toxicity or genotoxicity) of the chemical mixture, rather than concentrations of individual compounds. Both prokaryotic (no nucleus or membrane-bound organelles) and eukaryotic (with membrane-bound nucleus) cells are used. For on-line measurements prokaryotic cell assays are favoured because eukaryotic cells need a sterile environment to survive. For grab samples disposable monitors are available. The relevance for human health risks of prokaryotic cells is under debate. No on-line detection instrument based on eukaryotic cells is known. For source water protection and early warning systems in distribution networks prokaryotic cell assay instrumentation is commercially available and can be used with in-line dechlorination and feed options. Typical detection limits are several µg/L up to tens of µg/L. In order to account for metabolic processes in mammals, often S9-fraction is added to the samples. S9-fraction is derived from homogenized liver containing P450 enzymes which are responsible for the degradation of toxic compounds.

3.3.1.3 Organisms
Fish, water flea (Daphnia), mussel and algae monitors are commonly used to monitor intake points of surface water.
Table 3-2 provides an overview of the compound groups to which certain organisms are sensitive, and their detection levels.

Table 3-2: Sensitivity of in use organisms for different compound groups

<table>
<thead>
<tr>
<th>Organism</th>
<th>Detection principle</th>
<th>Compound group</th>
<th>Detection level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algae, (Chlorella Scenedesmus)</td>
<td>Fluorescence deviation</td>
<td>Herbicides</td>
<td>Low µg/L</td>
</tr>
<tr>
<td>Daphnia</td>
<td>Movement</td>
<td>Pesticides, i.p. insecticides / cholinesterase inhibitor</td>
<td>Low µg/L</td>
</tr>
<tr>
<td>Mussel (Dreissena polymorpha)</td>
<td>Schell gap</td>
<td>Organochlor compounds, metals,</td>
<td>µg/L</td>
</tr>
<tr>
<td>Luminescence bacteria (Vibrio fischeri)</td>
<td>Fluorescence</td>
<td>Aromatics, chlorbenzenes, pesticides, halogenated hydrocarbons</td>
<td>µg-mg/L</td>
</tr>
</tbody>
</table>

With feed option and in-line dechlorination options, these monitors have operational value from source to tap. Research is needed on their use in chlorinated water. [De Hoogh et al. 2006, Mikol et al. 2007, Penders et al. 2006, Wagenvoort et al. 2005]

Over the past few years progress has been made to reduce the false positive alarm rate of biological monitors. A working group is currently discussing adaptation of the ISO standard 15839:2003, “on-line sensors/analysing equipment for water – Specifications and performance tests” for whole organism biosensors, to distinguish between continuous and batch-wise measurements [De Hoogh et al. 2006].

3.3.2 Physical sensors

Identification of chemicals based on their physical properties, in particular spectroscopy, is a rapidly developing field [Luypaert et al. 2003, Ellis and Goodacre, 2006, Beckhoff et al. 2006]. The following spectroscopic methods are prominent: IR, Raman, X-ray fluorescence and UV-VIS. For the water matrix UV-VIS spectrometry is the spectroscopy method used [S::can]. Based on newly developed data analysis techniques more information is extracted from the spectrograms [Chen et al. 2006, Greffe et al. 2006, Xie et al. 2005, Yu et al. 2004]. There are two main drawbacks.

- Linearity between the concentration of a compound and its absorbance performance differs from compound to compound. Therefore it is hard to identify a compound based on a single spectral wavelength. Only the ratio between different wavelengths can assist identification.
- Secondly, only a small fraction of the potential compound array in water absorbs light with wavelengths from 190 to 850 nm. This means that UV-VIS spectroscopy must be combined with other techniques to cover a larger compound spectrum. IR, Raman and X-ray fluorescence spectroscopy are new techniques for on-line
chemical water quality monitoring, but many challenges must be overcome before these techniques can be used routinely.

Electronic-tongues are a group of sensors based on various physical detection principles such as ion-selectivity, mass balance, voltammetry and resistance. The water is sent through an array of sensors with different interface layers and the results are interpreted with multivariate analysis methods. A novel approach by Lindquist [2007] attempts to provide a kind of integral water quality assessment without reference to the concentrations of specific analytes.

A major advantage of physical techniques is the prospect of reduced analytical reagent use. Future research and developments have to prove the feasibility of this prospect.

3.3.3 Analytical chemistry

Many sophisticated techniques have been developed and used for the identification and quantification of compounds in water at the laboratory scale. These include, Gas Chromatography-Mass Spectroscopy (GC-MS), High Performance Liquid Chromatography-Mass Spectroscopy (HPLC-MS), isoelectric focussing (IEF) and capillary electrophoresis (CE).

The miniaturisation of these techniques is progressively investigated [Gad-el-Hak 2006, Silvertand et al. 2006, Taylor et al. 2000]. Although examples of commercial systems for on-site detection exist, a lot of research is still needed to develop ready-for-use on-line monitoring systems. Pre-treatment for on-line analysis is a critical challenge. The high costs of available systems and the need for intensive maintenance of sensors are also still barriers to their widespread application.

Despite the high costs, on-line HPLC and GC are in use in The Netherlands. Tables 3-3 and 3-4 present the compounds routinely analysed in The Netherlands with their corresponding limit of quantification (LOQ) by HPLC-UV and GC-MS respectively.

Table 3-3: Compounds monitored with automated HPLC-UV

<table>
<thead>
<tr>
<th>Compound</th>
<th>LOQ (µg/L)</th>
<th>Compound</th>
<th>LOQ (µg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phenylurea herbicides (13 specific compounds)</td>
<td>0.2</td>
<td>2,6-dimethylpyridine</td>
<td>1</td>
</tr>
<tr>
<td>Carbendazim</td>
<td>0.2</td>
<td>2, 6-dichlorobenzamide (BAM)</td>
<td>0.2</td>
</tr>
<tr>
<td>Carbamazepine</td>
<td>1</td>
<td>Phthalates (four compounds)</td>
<td>0.2 – 1</td>
</tr>
<tr>
<td>Tetra Acetyl Ethylene Diamine (TAED)</td>
<td>1</td>
<td>Organophosphates (2 compounds)</td>
<td>0.2</td>
</tr>
<tr>
<td>N-butylbenzene sulfonamide</td>
<td>1</td>
<td>Triazine pesticides (two compounds)</td>
<td>0.1</td>
</tr>
<tr>
<td>Triphenylphosphine oxide (TPPO)</td>
<td>1</td>
<td>Barban</td>
<td>0.2</td>
</tr>
<tr>
<td>Compound</td>
<td>LOQ (µg/L)</td>
<td>Compound</td>
<td>LOQ (µg/L)</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>------------</td>
<td>-------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>N-butylbenzenesulfonamide</td>
<td>0.2</td>
<td>Triphenylphosphine oxide (TPPO)</td>
<td>0.2</td>
</tr>
<tr>
<td>Fenanthrene</td>
<td>0.2</td>
<td>Organophosphates (three compounds)</td>
<td>0.2</td>
</tr>
<tr>
<td>Pirimicarb</td>
<td>0.2</td>
<td>Triazine pesticides (eight compounds)</td>
<td>0.2</td>
</tr>
<tr>
<td>Caffeine</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3-4: Compounds monitored with automated GC-MS

3.4 Technologies to detect microbial contaminants

The challenge in water systems is to detect and identify a specific pathogen among $10^{5-7}$ other harmless microbes per litre of water. Concentration techniques for increasing microbial numbers are essential for increasing the chances of detection and identification. Sample pretreatment to improve recovery rate whilst minimising the time for concentration is a major challenge.

Laboratory, as well as on-site detection, methods have been developed for the identification and quantification of a range of micro-organisms in water samples. Technologies used are:

3.4.1 Molecular biology assays

Molecular biology assays are based on recognition of specific DNA sequences of micro-organisms. Their specificity is very high, resulting in an excellent discrimination between closely related micro-organisms. So far, no other detection methodology has shown a similar performance.

The development of protein nucleic acids (PNA) and nucleic acid sequence based amplification (NASBA) assays increases the possibilities for on-line monitoring of micro-organisms. Unique characteristics such as the thermal stability and the enzymatic cleavage resistance of PNA’s opens pathways to robust and reliable methods based on, for example, fluorescence in situ hybridization (FISH).

In the near future the possibility of developing “discontinuous” measurement technologies looks promising. However, continuous on-line measurements are much more difficult to develop due to the affinity interaction principle. As described in paragraph 3.4, reuse of the sensor is only possible after replacement of reagents or regeneration of reporter molecules. Detection principles like refractive index change, fluorescence measurements or mass balances can be used to quantify affinity interactions. A drawback of this technique is that it does not distinguish between viable and non-viable micro-organisms.
3.4.2 ATP measurements
Adenosine triphosphate (ATP) is the energy carrier of living organisms. As soon as an organism dies ATP concentrations rapidly decreases. On-site analyses are available to determine the ATP concentration of a grab sample within a couple of minutes. The signal provided is an approximate indication of the biomass content of the water sample. The concentration of ATP in micro-organisms depends on species, strain, metabolic activity and environmental factors. The main drawback of ATP measurements is the ambiguous relation between the measured signal and the numbers and activity of the organisms present. Another consideration regarding on-line application is the cost. The enzymes required for the analysis are very expensive and consumption is high. Separation of cell-bound ATP from free ATP and removal of any eukaryotic cells, would provide a more reliable estimate of bacterial numbers, particularly if this was an automated process. Combined with specific microbial identification techniques this may yield a powerful tool in the future (cf. paragraph 3.9).

3.4.3 Antibody assays
Antibodies can be manufactured to recognise specific protein and carbohydrate structures, a principle that can be exploited to identify micro-organisms. The outside of micro-organisms consists of various protein and carbohydrate molecules and some of these are species or strain-specific. The main drawbacks to antibody assays are the requirements for reagents and vulnerability to matrix effects of the sample. Antibody assays are also less selective than molecular biology assays, due to the differences in specificity of proteins and carbohydrates in relation to DNA. The cross reactivity of antibodies is much higher than that of DNA.

3.4.4 Physical detection principles
There is an increasing interest expressed in the scientific literature for utilising physical principles to detect micro-organisms [Carlson et al. 2006, Chen et al. 2006, Hasan et al. 2005, Schneider 2006, van den Broeke 2005, Xie et al. 2005, Yu et al. 2004]. Although this area of research is at an early stage of development, it has promise. Three highlights are discussed below.

3.4.4.1 Turbidity
Turbidity is the light reflected by suspended particles under an angle of 90 degrees. It cannot be directly equated to suspended solids because white particles reflect more light than dark-coloured particles and many small particles will reflect more light than an equivalent large particle.

Turbidimeter technology is used by many utilities to monitor filter water quality. Hach-Lange has developed this technology for event monitor to identify if high concentrations of microorganisms are released into water which normally contains lower numbers of particles. Theoretically, the intentional introduction of pathogens in distribution networks could be detected, although this is a non-specific detection method and the sensitivity does not currently meet requirements. A variation on this theme will be discussed in paragraph 3.9.

3.4.4.2 Vibrational spectroscopy
This technology involves interpreting the spectra that are emitted from transitions between vibrational levels of a molecule following excitation by laser light. Molecules such as nucleic acids, cytoplasmic proteins, membrane lipids or cell wall components are the building blocks of micro-organisms and their exact composition is unique for each organism.
Vibrational spectroscopy is a non-invasive and reagentless method. Two methods are under investigation and are described briefly:

**(a) Raman spectroscopy**

The Raman effect is defined as light excitation due to inelastically of scattered light. Raman spectroscopy has recently been developed into two technologies for microbial detection. “Surface enhanced Raman-spectroscopy” is the identification of micro-organisms from the spectra produced at the surface of the organism which has reacted with antibodies. The combination of antibody and Raman spectroscopy increases the specificity of the identification.

The second technique is “Laser Tweezer Raman Spectroscopy” where an optical “tweezer” is used to ‘catch’ a micro-organism and then laser light is used to produce a Raman spectrum. Using this technique the discrimination between different strains of bacteria (Bacillus cereus, Enterobacter aerogenes, Escherichia coli, Streptococcus pyogenes, Enterococcus faecalis and Streptococcus salivarius) [Yu et al. 2004] and the germination of single Bacillus spores [Chen et al. 2006] have been reported.

**(b) FT-IR spectroscopy**

The mid-IR region covers the wavelength range from 4000 to 400 cm. The basic principle of the IR technique is that various organic functional groups absorb infrared light at specific wavelengths. Thus, since every organic molecule has a unique chemical structure, it also has a unique infrared spectrum. Biological samples are composed of proteins, carbohydrates, lipids and nucleic acids. Since these molecules contain functional organic groups, the IR spectrum produced consists of bands from all these components.

Infrared spectra are very complex and contain large amounts of information. To evaluate the data requires multivariate statistical analysis. In 2004 Yu et al. 2004] reported the identification of eight different micro-organisms in apple juice matrix which was based on FT-IR spectroscopy and chemometrics. The micro-organisms identified were, Enterobacter cloacae, Salmonella typhimurium, Enterobacter aerogenes, Salmonella choleraesuis, Serratia marcescens, Pseudomonas vulgaris, Vibrio cholerae, and Hafnia alvei.

Both techniques were presented as laboratory-based techniques. Recently, research has been initiated into the use of vibrational spectroscopy for the on-line detection of micro-organisms. The project “Tweezing and Raman spectroscopic sensing of bacteria in water using photonic crystal cavities” is being carried out within the Technological Top Institute Water in The Netherlands.

A general drawback of vibrational spectroscopy is that the molecular composition of a micro-organism depends on metabolic and environmental factors. These technologies have a future only if spectrum deviations caused by metabolic or environmental factors are smaller than the spectral deviations between strains.

**3.4.4.3 Multi-angle light scattering (MALS) technology**

MALS is a variation of turbidity measurements but instead of one light source, several light sources and angles of refraction are used. With proprietary algorithms, the shape, size, refraction index and internal structure of a particle can be deduced from the light scatter
patterns. In this technique micro organisms are more accurately detected and there are fewer false-positives produced compared to turbidity.

MALS identification of micro-organisms is less reliable than identification by vibrational spectroscopy. MALS technology is beginning to mature and commercial equipment is available.

3.5 Technologies to detect radiological contaminants

Only a few systems are commercially available for analysing grab samples for radiological contaminants. These systems have been developed for wastewater monitoring but could potentially be adapted for on-line monitoring of drinking water.

α and β radiation is difficult to detect in water due to their absorption by water molecules resulting in a very low level of free particles being detected. All monitoring systems reported are expensive and special expertise is required for operation and data analyses resulting in a low level of implementation at water utilities. This is probably also the reason that none of the systems have been verified by an official authority.

Water utilities fear radiolabels in their distribution networks due to this lack of detection possibilities.

3.6 Data, acquisition, analysis & mining

An extensive description on data acquisition and analysis is given in the EPA report “Technologies and techniques for early warning systems to monitor and evaluate drinking water quality: state-of-the-art review” [Hasan et al. 2005] (pages 37 – 41). It concludes that a system like supervisory control and data acquisition (SCADA) is indispensable to manage the huge amount of data produced by on-line measurement systems. Two challenges where future developments could improve sensor techniques are data analysis of sensor/detector signals and data mining.

3.6.1 Data analysis:

By increasing complexity of the physical and chemical analysis technology, the complexity of the data produced will also increase. The use of proven low-cost and online sensor technology in more locations in the drinking water production chain leads to varying quality of data in space and time. This data can transferred through a system (e.g. SCADA) to a more sophisticated processing system or if the data load is too large to transfer, some processing may be required at the sensor/detector. Developments in transfer of increasingly large datasets, would allow for more sophisticated statistical analysis and interpretation [Bukhari and LeChevallier 2006].

3.6.2 Data mining:

Water utilities collect vast amounts of data from on-line monitoring systems. These data are used for operational or regulatory purposes and can be stored in databases for many years. There have been very few investigations of the stored datasets to determine if they contain additional information or if the combined data has a higher value than the sum of the individual data.

A recent investigation has been performed on a dataset of Waternet, the Amsterdam water utility. Grefte et al. [2006] evaluated the contribution of data from multi-parameter, chemical
and biological measurements to define water quality. Data from samples taken over 14 years, at 200 sampling points for 250 different parameters were analysed. The authors indicated that, based on the data available, it is difficult to draw conclusions. Even with such a large dataset, they identified that there was too little data as not all parameters were measured at sufficient frequency. The low frequency is a consequence of the regulatory regime. The government determines whether a parameter should be measured with high or low frequency in order to satisfy their expectation of meeting water quality standards. In this example the low frequency of measurement does not allow more complex analysis to better define water quality. This indicates that the water company would have to intensify its monitoring activities to improve on its definition of water quality.

Data mining can assist in identifying monitoring gaps. Future research should pay attention to this subject.

3.7 Modelling

Page 41-51 of the USEPA report [Hasan et al. 2005] deals with issues like contaminant flow prediction and alert management systems, sensor placement, integrated water distribution modelling and data acquisition systems, data security and communication, and decision making. In summary, the report regards modelling as a useful tool to achieve front-end and back-end software solutions. Front-end solutions entail planning (installation, location, and operation of monitoring systems), while back-end solutions transform data from various locations into action-oriented knowledge.

Innovative elements in front-end software components include:
- A clear understanding of distribution system hydraulics including proper physical descriptions of contaminant mixing;
- A clear understanding of contaminant transport in a complex network of interconnected service mains;
- An a priori ability to assess system hydraulics with a view to:
  - Possible consequences of contamination events (e.g., health risks and costs)?
  - Optimal sitting of monitoring units to minimize such consequences.

Innovative back-end elements include development of algorithms capable of solving in real time:
- System hydraulics and contaminant transport equations, and
- Inverse equations to accurately localize the contaminant source.

The algorithms that must be developed represent an important part of a monitoring system’s “brain”. Other parts include decision-support software for managers to “interpret” data from the front- or back-end software platforms in order to facilitate a choice between their various risk management options. It may also include tools which provide better definitions of drinking water system hazards (intentional and unintentional), allowing water managers to plan effectively for “likely” threat scenarios rather than for all scenarios.

3.8 Technological innovation

A technological challenge is often overcome by combining the best of technologies from two or more fields. However researchers require a special mindset to think laterally or across boundaries. To assist in stimulating this mindset, several past examples are highlighted below.
• Purification and molecular biology
  A critical issue with regard to microbial contaminants is the concentration step. Recent innovations were triggered by attempts to combine knowledge from water purification technology with molecular biology. Solution: Sample large water volumes, apply membrane filtration and use molecular probes for pathogens trapped on the membranes.

• Biofilm research and toxicology
  Carlson et al. [2006] proposed detecting biofilm disturbances by toxic chemicals with turbidity sensors. Solution: This is a promising new application for a monitoring technique established long ago.

• Physics and chemistry or physics and microbiology
  High resolution data analysis facilitates the handling and evaluation of huge datasets which may contain specific information on chemicals and micro-organisms. Solution: Analyse historic datasets for extracting new information.

• Differentiation
  All analytical methods are primarily focused on exact determination of contaminant concentrations, but these are rarely relevant to operators. In many cases, operators prefer trigger values for regulated contaminants. Solution: Applying trigger values allows simplification of monitoring equipment and the possibility of reduced sensitivity.

• Data handling and daily operations
  Smart combinations of personal know-how and data acquisition, analysis & mining tools are desirable. Solution: Combine distribution network features, flow scheme information, sensor data, laboratory results and maintenance schemes in a Geographic Information System (GIS).

3.9 Conclusion
  There is currently a fast development in various sensors and on-line monitoring systems that may have clear and multiple benefits for water utilities such as lower costs and more information in time and space. However, many of the systems need to be developed further and are not tested in real world situations. There are still problems with robustness, sensitivity and repeatability.

Possible applications are in intake protection, control of operations, security, and informing customers. Currently, on-line sensors are most frequently for flow rate, turbidity, pH and water temperature. Other parameters include free chlorine, fluoride, spectral adsorption and biomonitor responses. The current performance of systems based on physical principles is rated higher then systems based on chemical or biochemical detection processes.

3.10 References
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System (AWACSS) - Part II: Intelligent, remote-controlled, cost-effective, on-line, water-monitoring measurement system, Biosens Bioelectron 20(8), 1509-1519


4 Inventory of utility experiences

Members of UKWIR, AwwaRF, BTO and GWRC were issued with a survey questionnaire to assess which physical, chemical and microbiological parameters were measured in the drinking water production chain (stored water, groundwater, surface water, through treatment, distribution and in finished treated water). Information was received from 52 water utilities in the USA, six water utilities in Australia and 16 water utilities in Europe (UK, Belgium and the Netherlands). Also water utilities were questioned on the amount and type of parameters already monitored on-line. The utilities identified which parameters were measured at the same location more than once a week, either by sampling and analysis in the laboratory or on-line and those parameters where research on existing sensor systems would be particularly worthwhile. A summary of the results is presented and discussed here.

4.1 Number of on-line measured parameters in various countries

Figure 4-1 presents the number of monitored on-line parameters by utilities in the US, Belgium & the Netherlands, United Kingdom and Australia.

![Figure 4-1: Number of parameters monitored on-line per country](image)

In the USA the majority of utilities measure between 4 and 6 parameters on-line. For Belgium and the Netherlands the number of on-line parameters is somewhat higher, 6 – 8. In the United Kingdom, on average, water utilities seem to monitor more parameters on-line (9-16), although numbers vary greatly between water utilities. The highest dispersion was obtained from the Australian survey and the average number of measured parameter is higher than in the USA, The Netherlands & Belgium. Instruments are used throughout the water production and distribution processes.
4.2 Top 10 on-line monitoring parameters

The top 10 parameters measured on line are listed in table 4-1 for the USA, Belgium and the Netherlands, United Kingdom and Australia respectively.

Table 4-1: Top 10 parameters monitored on line

<table>
<thead>
<tr>
<th>Rate</th>
<th>Parameter</th>
<th>USA (%)</th>
<th>n = 52</th>
<th>Parameter</th>
<th>B &amp; Ni (%)</th>
<th>n = 10</th>
<th>Parameter</th>
<th>UK (%)</th>
<th>n = 7</th>
<th>Parameter</th>
<th>Australia (%)</th>
<th>n = 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flow rate</td>
<td>100</td>
<td>52</td>
<td>Flow rate</td>
<td>100</td>
<td>10</td>
<td>Flow rate</td>
<td>100</td>
<td>7</td>
<td>Flow rate</td>
<td>100</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>Turbidity</td>
<td>89</td>
<td></td>
<td>Turbidity</td>
<td>100</td>
<td></td>
<td>Turbidity</td>
<td>100</td>
<td></td>
<td>Turbidity</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>pH</td>
<td>79</td>
<td></td>
<td>pH</td>
<td>90</td>
<td></td>
<td>Turbidity</td>
<td>100</td>
<td></td>
<td>Turbidity</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Water temperature</td>
<td>77</td>
<td></td>
<td>Oxygen</td>
<td>90</td>
<td></td>
<td>Chlorine</td>
<td>100</td>
<td></td>
<td>Chlorine</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Conductivity</td>
<td>39</td>
<td></td>
<td>Water temperature</td>
<td>80</td>
<td></td>
<td>Water temperature</td>
<td>80</td>
<td></td>
<td>Water temperature</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Particle count</td>
<td>37</td>
<td></td>
<td>Conductivity</td>
<td>60</td>
<td></td>
<td>Conductivity</td>
<td>72</td>
<td></td>
<td>Conductivity</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Fluoride</td>
<td>21</td>
<td></td>
<td>Ca/Mg/Hardness</td>
<td>50</td>
<td></td>
<td>Pressure</td>
<td>72</td>
<td></td>
<td>Conductivity</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Oxygen</td>
<td>17</td>
<td></td>
<td>Biomonitors</td>
<td>50</td>
<td></td>
<td>Pressure</td>
<td>72</td>
<td></td>
<td>Pressure</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Chlorine</td>
<td>14</td>
<td></td>
<td>Particle count</td>
<td>30</td>
<td></td>
<td>Oil in water</td>
<td>57</td>
<td></td>
<td>Particle count</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>TOC</td>
<td>14</td>
<td></td>
<td>Spectral absorption</td>
<td>30</td>
<td></td>
<td>Nitrate</td>
<td>57</td>
<td></td>
<td>Total chlorine</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

The top three parameters for all countries are the same, and are the non-specific parameters flow rate, turbidity and pH. In addition water temperature is measured frequently in all countries. Specific data on chemical, microbiological or radiation are not gathered by on-line monitoring, except for the use of biomonitors in Belgium and the Netherlands.

In the UK, USA and Australia chlorine and fluorine are frequently measured on line. As utilities in the Netherlands do not add chlorine or fluoride, there is no need to monitor these parameters.

4.3 Performance of on-line measurements

Table 4-2 summarises the performance of on-line measurements for 14 parameters for the USA, Belgium & The Netherlands and Australia respectively. The number of utilities that measure the parameter given first, followed by the percentage of utilities that qualified the on-line measurement as “good”. The remaining percentages are the sum of the qualifiers average, poor and bad.

Table 4-2: Summary of the performances of on-line measurements for 14 parameters (US, Netherlands, Belgium and Australian data).

<table>
<thead>
<tr>
<th>Parameter</th>
<th># Utilities USA</th>
<th>% &quot;GOOD&quot;</th>
<th># Utilities B &amp; Ni</th>
<th>% &quot;GOOD&quot;</th>
<th># Utilities Australia</th>
<th>% &quot;GOOD&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate</td>
<td>52</td>
<td>79</td>
<td>10</td>
<td>73</td>
<td>6</td>
<td>83</td>
</tr>
<tr>
<td>Turbidity</td>
<td>46</td>
<td>76</td>
<td>10</td>
<td>83</td>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>pH</td>
<td>41</td>
<td>66</td>
<td>9</td>
<td>74</td>
<td>6</td>
<td>100</td>
</tr>
<tr>
<td>Water temperature</td>
<td>40</td>
<td>84</td>
<td>8</td>
<td>82</td>
<td>6</td>
<td>100</td>
</tr>
<tr>
<td>Conductivity</td>
<td>20</td>
<td>64</td>
<td>6</td>
<td>92</td>
<td>5</td>
<td>80</td>
</tr>
<tr>
<td>Oxygen</td>
<td>9</td>
<td>53</td>
<td>9</td>
<td>79</td>
<td>3</td>
<td>33</td>
</tr>
<tr>
<td>Particle count</td>
<td>19</td>
<td>40</td>
<td>3</td>
<td>83</td>
<td>4</td>
<td>50</td>
</tr>
<tr>
<td>Spectral absorption</td>
<td>6</td>
<td>80</td>
<td>3</td>
<td>60</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>Fluoride</td>
<td>11</td>
<td>75</td>
<td>0</td>
<td>n.a.</td>
<td>5</td>
<td>80</td>
</tr>
<tr>
<td>Chlorine</td>
<td>7</td>
<td>81</td>
<td>0</td>
<td>n.a.</td>
<td>6</td>
<td>100</td>
</tr>
<tr>
<td>Ca/Mg/Hardness</td>
<td>0</td>
<td>n.a.</td>
<td>5</td>
<td>33</td>
<td>0</td>
<td>n.a.</td>
</tr>
<tr>
<td>Biomonitors</td>
<td>0</td>
<td>n.a.</td>
<td>5</td>
<td>0</td>
<td>1</td>
<td>100</td>
</tr>
</tbody>
</table>
Table 4-3 summarises the performance of on-line measurements for the 14 parameters for the UK. It is of interest that on-line equipment was rated in a similar manner on its performance irrespective of where the instrument was located in the water production process.

Table 4-3: Summary of the performances of on-line measurements for 14 parameters (UK data).

<table>
<thead>
<tr>
<th>Parameter monitored on-line</th>
<th>Stored Water</th>
<th>Ground Water</th>
<th>Surface Water</th>
<th>Process Treatment</th>
<th>Final Water</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Rate</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Turbidity</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
</tr>
<tr>
<td>PH</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
</tr>
<tr>
<td>Chlorine</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
</tr>
<tr>
<td>Pressure</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Water Temperature</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Conductivity</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Iron</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Nitrate</td>
<td>Good/Ave</td>
<td>Good/Ave</td>
<td>Good/Ave</td>
<td>Good/Ave</td>
<td>Good/Ave</td>
<td>Good/Ave</td>
</tr>
<tr>
<td>Oil on water</td>
<td>Poor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ammonium</td>
<td>Average</td>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orthophosphate</td>
<td></td>
<td></td>
<td>Good/Ave</td>
<td>Good/Ave</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manganese</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>Average</td>
<td>Average</td>
<td>Average</td>
<td>Average</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In general the performance of systems based on physical measuring principles is qualified better than systems that make use of chemical or biochemical measuring principles.

More detailed descriptions of the monitoring equipment used and their performance rating are provided for each country in appendix IV.
5 Research strategy for Sensors and Early Warning Systems

5.1 Introduction

During the research strategy workshop “on-line and real-time monitoring of contaminants in water” held at Kiwa Water Research on March 22-23, 2007, representatives from vendors, water utilities and GWRC-members defined knowledge gaps and research needs. The input to the Strategic workshop was derived from the Country workshops (Appendixes I – II), discussions with utility representatives in the Netherlands and the state of the art review on sensor technologies (Chapter 3). Further details of the Strategic Workshop are presented in Appendix III.

The main conclusions from the Strategic workshop are:

Workshop participants identified several areas for improvement:

- monitoring equipment should better fit practical utility needs and should be easy to operate and maintain;
- verification schemes should sufficiently match utility practices;
- available sensor technologies should link to water quality regulations;
- technologies and practices should be developed to manage the large quantities of data and translate these into information for operational processes;
- exchange of information and experience with the use of sensors between water utilities, manufacturers and pilot researchers.

The following five areas for future research and activities have been identified:

- More in-depth review of current on-line monitoring practices to meet utility needs. Although this project has set a first valuable step, the workshop concluded that a more in-depth review on utility drivers and needs for sensors including a costs-benefits analysis is needed. More countries should be involved in this study.
- Consistency of testing. The protocols for testing on-line measurement equipment used by vendors, pilot researchers and water utilities do not match. All workshop participants identified the need for harmonisation in testing protocols in the chain from development to product use. An advantage is a shorter time to market, appreciated by both vendors and water utilities.
- Linking sensor development to water quality regulations. Data produced by on-line monitoring systems provide real time information on water quality. This differs from the established practice of laboratory analysis which can only confirm that the water is of satisfactory quality, in many cases, after the water has been distributed. On-line, real-time monitoring is an upcoming technology and will have implications on the regulatory framework for assessing water quality.
- Data handling. Reliance on water monitoring and alarm systems have increased due to the greater complexity of treatment processes, increased automation, reduced staffing, and the regulatory and societal drivers to provide higher levels of security and safety. Inevitably, alarms have increased, making the job of responding correctly more difficult. The proposed project will examine sensor and (statistical) data handling and analysis tools to transform data into information that can be used as basis for risk management.
• Establishment of Community of Practice on Sensors in the Water Industry. Exchange of information and know-how on the development of sensors and practical experience with the use of sensors is of the utmost importance to the water industry to be able to use the full potential of the technology available (today and in the future). Therefore a Community of Practice on sensors is proposed with the task of facilitating information exchange by an annual workshop and a web-based platform.
5.2 Research proposal 1: More in-depth review of current on-line monitoring practices to meet utility needs.

<table>
<thead>
<tr>
<th>Project Title:</th>
<th>More in-depth review of current on-line monitoring practices to meet utility needs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name of Proposer &amp; Affiliation:</td>
<td></td>
</tr>
<tr>
<td>Collaborators:</td>
<td>Water utilities, Vendors, Researchers</td>
</tr>
<tr>
<td>Estimated Total cost of Research (Euro)</td>
<td>2007</td>
</tr>
<tr>
<td></td>
<td>600,000</td>
</tr>
</tbody>
</table>

Justification:

Background:
Utilities employ on-line monitoring in response to drivers/needs such as regulation, customer expectations, process control, security cost/benefit, etc. Often, the industry researchers, developers, manufacturers, and even utilities do not understand the connection, leading to inappropriate applications and failures that in total, slow down the progress of on-line monitoring within the industry.

The lack of a shared consolidated reference on good on-line management practices similarly leads to failures and lack of progress.

A clear, international state-of-the-art document and set of research needs developed by the industry is not available.

For each of the six countries—Netherlands, U.S., Australia, Great Britain, Germany, and Italy—the on-line monitoring practice employed by six leading utilities will be assessed. For each country, the 2–3 day assessment would be carried out by a team composed of two to three utility representatives (two domestic, one international), one manufacturer, one researcher, and one consultant. All participants except consultants will volunteer their time for this work. The assessments would be carried out according to a standard protocol based on the principle of the Composite Correction Program.

- Different types of utilities representing river, lake, groundwater systems would be chosen based on their prevalence in the country and their use of on-line monitoring
- Applications at source, treatment, and in distribution will be addressed

A report per utility would be prepared and reviewed on site and later consolidated (no utility names used) in a country and 6-country international version addressing:

- On-line applications and drivers/needs, including cost/benefit
- Good On-Line Monitoring Practices
- Knowledge gaps and research needs
| Consequences if work not carried out: | • The rationale for on-line application will remain unclear.  
• Continue to develop the application of on-line monitoring without a sound foundation based on drivers and needs  
• The lack of shared Good On-Line Management Practices will impede the progress of implementing on-line monitoring equipment in the industry  
• Research needs will not be well understood |
| Benefits to be achieved: | • Allow confident adoption of on-line monitoring choices based on drivers/needs with a global background perspective  
• Allow choices that will provide optimum use of resources. Good on-line monitoring sensor practices will allow better use of economic resources  
• The project will give rational direction to researchers, developers and manufacturers |
| Objectives: | **Aiming to achieve:** What is currently being monitored in water utilities internationally and the rationale based on drivers and needs including cost benefits?  
**Specific questions answered:**  
• What approaches are used by utilities?  
• What is the baseline of industry state of the art?  
• What are Good On-Line monitoring practices?  
• What are the knowledge gaps and research needs?  
**Tasks set for contractor:**  
• Develop a standardized assessment protocol based on the Composite Correction Protocols to determine drivers, on-line monitoring in response to drivers, best practices and gaps/needs  
• Work with country-specific research organization to develop assessment team and utilities to be assessed  
• Facilitate assessment travel by consultant & volunteers  
• Write up consolidated country reports and international report  
**Deliverables:**  
• Six-country state-of-the-art document  
• Good on-line monitoring practices document  
• Research needs and information gaps  
• Education of a core group of industry stakeholders in “on-the-ground” on-line monitoring  
**Completion date to maximize benefits:** This should be the first project to be carried out and be the foundation for future projects  
**Target audience for the output?**  
• Utilities – international and country – state of art – best on-line monitoring practices  
• Manufacturers – better understanding of the real world application of sensors  
• Researchers – needs based on drivers  
**Which groups should receive any reports resulting from this work?** All  
**Should the output be made available?** Yes |
be submitted for independent peer review to add authority to the work?
### 5.3 Research proposal 2: Consistency of Testing

<table>
<thead>
<tr>
<th>Project Title:</th>
<th>Consistency of testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name of Proposer &amp;</td>
<td></td>
</tr>
<tr>
<td>Affiliation:</td>
<td></td>
</tr>
<tr>
<td>Collaborators:</td>
<td>Water utilities, Vendors, Researchers</td>
</tr>
<tr>
<td>Estimated Total Cost of Research (Euro)</td>
<td>2007</td>
</tr>
<tr>
<td></td>
<td>25,000</td>
</tr>
</tbody>
</table>

**Justification:**

**Background:**
There are three stages of testing during the development of a monitoring system. The first tests are carried out by the vendors. Secondly pilot testing is performed at research institutes. Finally water utilities test the overall performance of a system.

During the workshop it was identified that the protocols for testing on-line measuring equipment do not satisfy the needs of all three groups of stakeholders. All stakeholders identified the need for harmonisation of the testing process from initial development through to product use. A major benefit is a shorter time to market, appreciated by both vendors and water utilities.

**Consequences if work not carried out:**
- Inconsistent product development.
- Development of technologies that do not meet the needs of utilities.
- Slower or failure to introduce new on-line measurement equipment.
- Limited advance of the science and concept of real-time monitoring.
- Resistance by utilities, vendors and researchers to invest in future testing and purchase of instruments.

**Benefits to be achieved:**

- **Political**
  - Control expectations of new products and their ability to perform.

- **Economic**
  - Facilitating the planning of appropriate resources and budgets needed for testing.
  - Decreasing the time to market

- **Technical**
  - Realistic application of the technology

**Objectives:**

---

Aiming to achieve: Guidance Manual of testing protocols for water utilities, vendors and researchers to follow in order to accept a new technology or equipment. E.g.
- Basic water quality parameters within which testing protocols apply
- Number of runs and testing duration
- Equipment expectations
- Estimation of the costs for operation and maintenance

Specific questions answered: Is the sensor technology ready for acceptance and deployment into water monitoring system? Has it been challenged with a uniform set of real-world operating conditions?

Tasks set for contractor:
- Collect information on vendors testing.
- Collect data and lessons learned from water utilities with operational sensor testing data.
- Review previous research and operational knowledge gained from research and testing organizations such as KWR, AwwaRF, NSF International.
- Collect information on water utility needs.
- Develop standardised procedures and protocols for equipment testing and evaluation


Completion date to maximise benefits: December 2008

Target audience for the output?
Water utilities, Vendors, regulatory authorities, knowledge institutes

Which groups should receive any reports resulting from this work?
All

Should the output be submitted for independent peer review to add authority to the work?
Yes
5.4 Research proposal 3: Data handling

<table>
<thead>
<tr>
<th>Project Title:</th>
<th>Data handling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name of Proposer &amp; Affiliation:</td>
<td></td>
</tr>
<tr>
<td>Collaborators:</td>
<td>Water utilities, Vendors, Researchers</td>
</tr>
<tr>
<td>Estimated Total Cost of Research (Euro)</td>
<td>2007</td>
</tr>
<tr>
<td></td>
<td>300,000</td>
</tr>
</tbody>
</table>

Justification:

Reliance on water monitoring and alarm systems have increased due to the greater complexity of treatment processes, reduced staffing levels and the regulatory drivers to provide higher levels of security and safety. Inevitably, the number of alarms has also increased dramatically, making the job of responding correctly more difficult. This can be a particular issue when dealing with alarms from unmanned sites at regional centres.

This project will aim to examine sensor and other utility data using data mining techniques including alarm settings, drawing on participants’ experience and best practice in other industries. Areas of particular interest are:

Typically, water professionals think of early warning detection systems as being a system of monitors connected through a SCADA system to warn of changes in water quality. These systems are limited by not having sensors that are specific or sensitive enough to detect all of the possible contaminants. These systems are also limited by the number of sensors that can be practically deployed in a water system.

Data from sensors alone will not provide accurate information for the true reason behind a contamination alarm. Computerized systems and databases are available that can contribute valuable information and lead to earlier detection of water contamination events. Sensor data could be verified against hydraulic and other available instrument data for better interpretation in order to reduce false contaminant alarms. E.g. valve position status can be linked with sensor responses - this allows a real overall consistent picture of water quality and control. Customer complaint calls, hospital and doctors’ office visits, sales of certain medicines, etc. can also contribute valuable information that, if integrated, could lead to earlier detection of water contamination. The challenge is to identify what data are available and how diverse datasets can be connected or combined to provide useful information.
Data from sensors alone will only provide limited information on the extent of contamination.

There is a lot of valuable data recorded by sensors that is not produced as an output. There may be value if this unused data can be combined or interpreted to provide additional information on contamination events. How to access and make use of this data is a major challenge and current knowledge / expertise in this area is lacking.

It is important to make sure available data are as accurate as possible; performance assessments of currently installed systems using data mining techniques could help identify monitoring gaps. Correlating this information from existing sensors together with additional information could be done for different parts of the water treatment and distribution systems to broaden the validation process.

Combinations of detection technologies can give synergism in the number of detected chemical and biological contaminants but also provide evidence for the identity of the actual compound – undertake a pilot study using a model system with heavy metals or other contaminants to simulate a contamination event as a test case.

<table>
<thead>
<tr>
<th>Consequences if work not carried out:</th>
<th>Sensor systems will not realise their full potential &amp; expectations without the additional information on the larger picture, sensor information is just more data! Utilities would lose confidence in online measurement systems.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Poor publicity of sensor products, i.e., cost/benefit ratio.</td>
</tr>
<tr>
<td></td>
<td>Increased water safety and security issues.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Benefits to be achieved:</th>
<th>Improved security of water treatment as it is expected that all participants will find areas where practice can be improved.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Improved operational efficiency and consequent cost savings through minimising unnecessary alarms and call-outs.</td>
</tr>
<tr>
<td></td>
<td>Better information for planning --- benchmark sensor/instrument data in a national context, information on best practice to support internal standards and methods.</td>
</tr>
</tbody>
</table>

- Political

- Economic

Increased safety

A reduction in the number of false alarms hence cost.
**Objectives:**

<table>
<thead>
<tr>
<th>Aiming to achieve:</th>
<th>There are three key areas for the project to address:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a) Benchmarking: Review a unified way of looking at all available utility data to eliminate false alarms in response to a pollution event. The data gathered will be analysed and reported as a benchmark review of international practice, using a number of appropriate indicators.</td>
</tr>
<tr>
<td></td>
<td>b) Development of best practice - Best possible use of currently installed system, improve reliability and trustworthiness by showing the real value/information. Methods for increasing the reliability of instrument data.</td>
</tr>
<tr>
<td></td>
<td>c) Future developments: Show the benefit/added value of applying a combination of sensor technologies for true identification of contaminants and show the synergism of selected measurement technologies. Options to be considered could include combining online data with process models to generate additional information.</td>
</tr>
</tbody>
</table>

| Specific questions answered: | • What the best approaches are for data mining  
• Can data mining techniques in combination with other parameters & detection approaches be used to produce true alerts for contaminants and reduce false alarms to an acceptable level? |

| Tasks set for contractor: | To Be Defined. |

| Deliverables: | A final report detailing the benefits of utility data integration using data mining techniques and assessment on the likely reduction in the number of false contamination alarms from installed sensor systems. Dissemination events to ensure knowledge transfer. |

| Completion date to maximise benefits: | It is anticipated that this study will take approximately three years and be completed in 2010. |

<table>
<thead>
<tr>
<th>Target audience for the output?</th>
<th>Water utilities, SCADA system producers, consulting firms &amp; software manufacturers</th>
</tr>
</thead>
</table>
| Which groups should receive any reports | • Utilities and Vendors.  
• Data Mining software producers |
resulting from this work?

Should the output be submitted for independent peer review to add authority to the work?  

Yes
5.5 Research proposal 4: Linking sensor development to water quality regulations

<table>
<thead>
<tr>
<th>Project Title:</th>
<th>Linking sensor development to water quality regulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name of Proposer &amp; Affiliation:</td>
<td></td>
</tr>
<tr>
<td>Collaborators:</td>
<td>Water utilities, Researchers</td>
</tr>
<tr>
<td>Estimated Total Cost of Research (Euro)</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>2008</td>
</tr>
<tr>
<td>100,000</td>
<td></td>
</tr>
</tbody>
</table>

**Justification:**

**Background:**
HPLC-MS, GC-MS, Total count, Gram staining, Classical- and Molecular identification etc. are established laboratory techniques used for water quality monitoring. The regulatory-driven monitoring is based on the performances of these techniques.

On-line real-time monitoring is an upcoming technology and will have implications on the regulatory framework for water quality monitoring.

**Consequences if work not carried out:**
Delayed introduction of new on-line monitoring systems for regulatory measurements

**Benefits to be achieved:**
- **Political**
  - Governmental support for on-line monitoring of water quality.
  - More accurate information on water quality
- **Economic**
  - More cost-effective monitoring and regulatory frameworks
- **Technical**
  - Better focus of sensor development based on regulatory needs

**Objectives:**

**Aiming to achieve:**
- Awareness at governmental agencies of the use of on-line monitoring for water quality.
- Adaptation of regulations for the use of on-line monitoring for water quality.

**Specific questions answered:**
- What are the regulatory issues concerning on-line monitoring of water quality.

**Tasks set for contractor:**
- Investigation of the legal impediments for the implementation of on-line water quality monitoring.
- Starting discussions with the government to address the legal
- Initiate new regulations in relation to on-line water quality monitoring.

<table>
<thead>
<tr>
<th>Deliverables:</th>
<th>Report with a progress description and initiatives for further/future research or actions.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Completion date to maximise benefits:</td>
<td>December 2008</td>
</tr>
</tbody>
</table>

| Target audience for the output?        | Equipment Manufacturers, vendors, water utilities and government agencies                |
| Which groups should receive any reports resulting from this work? | Manufacturers, Vendors, Water Utilities and Research organisations                       |
| Should the output be submitted for independent peer review to add authority to the work? | Yes                                                                                     |
5.6 Research proposal 5: Establishment of Community of Practice on Sensors in the Water Industry

<table>
<thead>
<tr>
<th>Project Title:</th>
<th>Establishment of Community of Practice on Sensors in the Water Industry</th>
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</thead>
<tbody>
<tr>
<td>Name of Proposer &amp; Affiliation:</td>
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<tr>
<td>Collaborators:</td>
<td>Water utilities, Vendors, Researchers</td>
</tr>
<tr>
<td>Estimated Total Cost of Research (Euro)</td>
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<td></td>
<td>100 K€</td>
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<tbody>
<tr>
<td>Background:</td>
</tr>
<tr>
<td>Exchange of information and know-how on the development of, and practical experience with the use of, sensors is of utmost importance to the water industry in order to derive the full potential of the technology available (today and in the future)</td>
</tr>
<tr>
<td>Consequences if work not carried out:</td>
</tr>
<tr>
<td>Reinventing the do’s and don’t all around the globe</td>
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<tr>
<td>Benefits to be achieved:</td>
</tr>
<tr>
<td>- Political</td>
</tr>
<tr>
<td>Credibility regarding product (water quality) and processes used by the water industry by showing global collaboration</td>
</tr>
<tr>
<td>- Economic</td>
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<tr>
<td>Leverage of resources</td>
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<tr>
<td>- Technical</td>
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<tr>
<td>Reliable information to support decisions and operations</td>
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<table>
<thead>
<tr>
<th>Objectives:</th>
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<tr>
<td>Aiming to achieve:</td>
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<tr>
<td>Development of a Community of Practice on Sensors in the Water Industry</td>
</tr>
<tr>
<td>Specific questions answered:</td>
</tr>
<tr>
<td>Tasks set for contractor:</td>
</tr>
<tr>
<td>• Setting up a Community of Practise on Sensors in the Water Industry</td>
</tr>
<tr>
<td>• Development of a web-based platform</td>
</tr>
<tr>
<td>• State of the art documents on sensor developments</td>
</tr>
<tr>
<td>• Organising annual workshops</td>
</tr>
<tr>
<td>• Workshop report</td>
</tr>
<tr>
<td>Deliverables:</td>
</tr>
<tr>
<td>The Community of Practice on Sensors in the Water Industry will be supported by:</td>
</tr>
<tr>
<td>• A web-base platform for exchange of information on the development and practical use of sensors in the water industry</td>
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<td>Completion date to maximise benefits:</td>
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<tr>
<td>--------------------------------------</td>
</tr>
<tr>
<td>Target audience for the output?</td>
</tr>
<tr>
<td>Which groups should receive any reports resulting from this work?</td>
</tr>
<tr>
<td>Should the output be submitted for independent peer review to add authority to the work?</td>
</tr>
</tbody>
</table>
6 APPENDIXES

I  Pre-workshop UKWIR, September 4, 2006
II Pre-workshop AwwaRF, February 27, 2007
III Research strategy workshop, March 22-23, 2007
IV Questionnaire synthesis
I. Pre-workshop UKWIR, September 4, 2006

a. Summary
UKWIR and KWR held a joint workshop on Monday, September 4th, 2006 at Queen Anne’s Gate in London. The aim of the Workshop was to develop an inventory of water suppliers needs. It was attended by 17 delegates plus the speakers with representation from 12 UK water companies. The main objectives of the Workshop were:

- To collect the experiences of water utilities using on-line sensors in the UK
- To determine current requirements for analytical monitoring in the UK water industry and assess what is suitable for on-line measurement
- To provide an opportunity for the researchers from KWR to present their findings on the review of sensors and get guidance on sensor needs from water utility experts in the UK
- To identify needs and knowledge gaps for UK water utilities.

Prior to the Workshop each attendee was issued a survey questionnaire to assess what physical, chemical and microbiological parameters were measured in stored water, groundwater, surface water, through treatment, final (finished treated water) and in distribution. The questionnaire had been developed jointly between UKWIR and KWR. The brief provided to delegates was to identify those parameters that were measured at the same location greater than once per week either by sampling and analysis in a laboratory or on-line. The responses were collated and a summary presented at the Workshop.

Workshop presentations
The morning’s programme for the Workshop was devoted to presentations by UKWIR, KWR and UK Water Companies.

A general welcome and introduction was given by Mike Farrimond of UKWIR. Theo Van den Hoven then outlined the specific scope, objectives and set up of the workshop. Bram van der Gaag provided feedback on the review and findings of the UKWIR/AwwaRF/KWR collaborative project ‘State-of-the-art real-time on-line monitoring of contaminants in water”. Several presentations covered the collective experiences and needs of UKWIR members. These were:

- Intake Protection Monitoring (Wendy Smalley, Thames Water)
- Status of Monitoring at a UK Water Company (Peter Barratt, Anglian Water)
- Monitoring in Distribution (John Procter, Yorkshire Water)
- 05/06 UKWIR Rapid Analytical project and other UK initiatives (David Holt, UKWIR)

In the afternoon session the findings of the survey questionnaire were presented. There then followed a facilitated discussion where delegates discussed the findings, recounted experiences and identified issues that need addressing.

The collated results of the survey are shown in the slides presented in section d. In each slide the code provides an overall view of the reliability of the instrumentation in providing good data based on the comments received.
Workshop Findings

In the UK on-line monitoring equipment was widely utilised for a number of physical and chemical parameters at all stages throughout the water supply process from raw water to distributed water. Many companies use well-established equipment for physical measurements such as flow, pressure, temperature, conductivity, pH and turbidity. Some chemical reaction derived monitors were also widely used, for example iron, manganese, aluminium, nitrate and chlorine. In general this equipment was considered as reliable.

For a number of parameters, spectral analysis, oxygen monitors, chlorophyll a, particle counts, ammonia and oil in water, the equipment was used at fewer locations in the supply process and deemed less reliable.

Some companies expressed interest in being able to monitor for, or having more reliable equipment for a range of parameters:
- Low-level organics
- Pesticides
- Hydrocarbons
- Bromates
- Ozone
- Total nitrogen
- UV 254
- Nitrate
- DOC
- THMs
- On-line bacteria measurement

Water Companies also expressed the view that new instruments coming to market were not thoroughly tested for the environments in which they were to be exposed. In many cases the water company had to undertake its own trials to demonstrate the reliability and determine the maintenance frequencies of the equipment at one or more test sites. There appeared to be little exchange of information on instrument testing between water companies.

Water companies required highly trained staff to maintain a range of different equipment for monitoring various parameters.

In conclusion the main findings were:
- Intake protection and monitoring through treatment continue to be the focus for on-line monitoring
- One UK water company had considerable experience in on-line water quality monitoring in distribution
- Reliability of instruments was a major characteristic identified by many water companies
- The survey confirmed that those parameters currently monitored were still key requirements
- Drinking Water Safety Plans were seen as a driver for more monitoring of raw waters and treatment processes
b. Agenda

**UKWIR/KWR Workshop**

'STATE OF THE ART' REAL-TIME ON-LINE MONITORING OF CONTAMINANTS IN WATER

September 4th, 2006

1 Queen Anne’s Gate, London

**Agenda**

10.00 Welcome and coffee

10.15 Introduction to workshop and link to UKWIR research programme (*Mike Farrimond, UKWIR*)

10.30 Scope, objectives and set up of the workshop (*Theo van den Hoven, KWR*)

10.45 First results of the collaborative project (*Bram van der Gaag, KWR*)

11.15 Experiences and needs of UKWIR members
   - Intake Protection Monitoring (*Wendy Smalley, Thames Water*)
   - Status of Monitoring at a UK Water Company (*Peter Barratt, Anglian Water*)
   - Monitoring in Distribution (*John Proctor, Yorkshire Water*)
   - Output from 05/06 UKWIR Rapid Analytical project and other UK initiatives (*David Holt, UKWIR Project Manager*)

12.30 Lunch

13.15 Facilitated discussion on needs
   - Feedback from Questionnaire (*David Holt*)
   - General Discussion

15.00 Tea & Coffee

15.15 Follow up (*KWR*)

15:45 Synthesis and conclusions (*UKWIR, KWR*)

16.00 Close
c. List of participants

<table>
<thead>
<tr>
<th>Name</th>
<th>Name</th>
<th>Organisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peter Barratt</td>
<td>Peter Boruszenko</td>
<td>Anglian Water</td>
</tr>
<tr>
<td>Sarah Davies</td>
<td>Mike Farrimond</td>
<td>DCWW</td>
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<tr>
<td>Paul Gaskin</td>
<td>David Holt</td>
<td>Yorkshire Water</td>
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<tr>
<td>Mike Farrimond</td>
<td>Ruth Nelham</td>
<td>UKWIR</td>
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<tr>
<td>John Proctor</td>
<td>Chris Rockey</td>
<td>DCWW</td>
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<tr>
<td>Catherine Jones</td>
<td>Ian Skilling</td>
<td>Mid Kent Water</td>
</tr>
<tr>
<td>Mike Mooney</td>
<td>Wendy Smalley</td>
<td>South Staffordshire Water</td>
</tr>
<tr>
<td>John Proctor</td>
<td>Craig Tarft</td>
<td>South West Water</td>
</tr>
<tr>
<td>Kal Sidhu</td>
<td>Greg Tate</td>
<td>Veolia Water Partnership</td>
</tr>
<tr>
<td>Theo van den Hoven</td>
<td>Oliver Twydell</td>
<td>United Utilities</td>
</tr>
<tr>
<td>Bram van der Gaag</td>
<td>Doug Whitfield</td>
<td>South East Water</td>
</tr>
</tbody>
</table>
d. Presentations
Introduction

Dr Mike Farrimond
UKWIR Director

Project Background

- UKWIR Studies
  - 05/06 – “Rapid Analytical Response in Emergency Situations”
  - 06/07 – “Risk Studies and intake protection”
- Collaborative Review
  - ‘State of the Art’ Real-time on-line monitoring of contaminants in water
  - Partners, UKWIR, AWWARF and Kiwa

Project Objectives

- Undertake review of what analysis is needed.
- Determine
  - what is available
  - what needs development.
  - Including whole life costs, effectiveness, reliability, VFM, accuracy etc.
- Involve regulator to seek views on developing a programme of on-line monitoring as overall part of systems management strategy (fit with WSP)

Project Management

- Contractors: Kiwa
- UKWIR Project Client: Dr Arnold Bates, Bristol Water
- UKWIR Project Management: Dr David Holt, Thames Water
- Steering Group members:
  - John Hayley, Yorkshire Water
  - Peter Barratt, Anglian Water
  - Frank White, United Utilities
  - Steve Smith, Wessex Water
  - anothers

Today

- Workshop format
- Capture your views on needs
- Spreadsheet completion

Agenda

- 10.15 Introduction to workshop
- 10.30 Scope, objectives and set up of the workshop (Kiwa)
- 10.45 First results of the GWRC collaborative project (Kiwa)
- 11.15 Coffee & Tea
- 11.30 Experiences and needs of UKWIR members (UK Water Companies)
- 12:30 Lunch
- 13:30 Facilitated discussion on needs (All)
- 16:00 Close
Scope, objectives and set up of the workshop

UKWIR, London
September 4th, 2006
Theo van den Hoven

Safe drinking water
Meeting regulator and customer expectations

Starts with robust design (multibarriers) and proper operations!

Safety by risk management
Analysing and minimising risks for water quality and public health

Know your catchment
Know your river/river
Know your raw water
Know your treatment
Safeguard the distribution system
Safeguard the household plumbing
Safe drinking water

On-line water quality monitoring can assist .... Quality control before water is consumed

Sensors and Early Warning Systemen
Intake protection
Process Control
Terror

Sensor for treatment performance

Sensors for source monitoring
Algae toximeter

Real-time on-line monitoring of contaminants in water
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May 16, 2008
Booming developments, lots of promises but what is reality?

Current situation:
- periodical samples + laboratory analyses
- use of sensors for limited number of parameters
- requirements of users often not met with available systems

Advances in technology (ICT, microelectronics, a.o.)
- new and significantly enhanced sensor capabilities
- on-line monitoring water quality real possibility

UKWIR, AwwaRF, Kiwa and other GWRC partners have expressed the desire to explore opportunities

Joining forces
Global Water Research Coalition

Monitoring, sensor and communication technology identified as key issue by WSSTP

The project
Understand and utilise opportunities

- Bring together state-of-the-art reviews
- Collect experiences and needs from water suppliers
- Develop roadmap on sensor research and development
- Present results in international seminar (January 2007)

Today’s workshop

- Inventorise UKWIR member needs and experiences
- Present project results until now
- Identify opportunities
First results of the GWRC collaborative project
UKWIR, London
September 4th, 2006

Monitoring, Definition

Any kind of acquisition or collection of data on a certain state, activity or process by means of a technical device, an observation system or any other surveying method to assess the current status of the chosen parameters and changes over time.

Monitoring issues

- Data
  - Type of data needed
- Technical device
  - Laboratory equipment
  - Sensors, detectors
- Current states
  - Real-time
  - Near real-time
  - 24 hours
  - Week
- Changes over time
  - Access to historical data

Present situation

- Laboratory measurements
  - Chemical analyses
    - Aorganic: HPLC-MS, GC-MS, ICP-MS, etc.
    - Organic: HPLC-MS, GC-MS, ICP-MS, etc.
  - Microbiological
    - Total count, Gram staining, Classical and Molecular Identification etc.
- On-line Real-time
  - pH, Conductivity, O₂, TOC (total organic compounds), DOC (dissolved organic compounds), UV, Temperature, Pressure, Turbidity etc.

Present situation satisfactory?

- Consumers safety?
- Optimized process?
  - Overkill or cost effective
- New technologies under development

EPA technology survey EWS

- EPA Report
  - December 2005

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May 16, 2008
6. Technologies that Detect Chemical Contaminants for Early Warning Systems

6.2 Available Technology
- Gas Chromatography
- Enzyme-Based Detection
- Biosensors
- Gas Chromatography

6.2.1 Detection of Arsenic
- Gas Chromatography
- Enzyme-Based Detection
- Biosensors
- Gas Chromatography

6.2.2 Detection of Cyanide
- Gas Chromatography
- Enzyme-Based Detection
- Biosensors
- Gas Chromatography

6.2.3 Gas Chromatography
- Enzyme-Based Detection
- Biosensors
- Gas Chromatography

6.3 Potentially Adaptable Technology
- Enzyme-Based Detection
- Organism-Based Biosensors
- Infrared Spectroscopy
- X-ray Fluorescence
- Ion Mobility Spectroscopy
- Microchips for Portable Chemical Sensors
- Microchip Surface Acoustic Wave (SAW) Technology
- Microchip Chemiresistors

6.4 Emerging Technology
- Enzyme-Based Detection
- Organism-Based Biosensors
- Eukaryotic Cell-Based Biosensors
- Fiber Optic Cable-Based Sensors
- Ion Mobility Spectroscopy (IMS)
- Surface Acoustic Wave (SAW) Technology
- Raman Spectroscopy

7. Technologies that Detect Microbial Contaminants for Early Warning Systems

7.2 Available Technologies
- Immunoassays
- Detection of Bacterial - ATP
- Flow Cytometry- and Micro-Flow-Based Technology
- Bioparticulate Monitors - Light Scattering Technology
- Bioparticulate Monitors - Light Scattering Technology
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- Bioparticulate Monitors - Light Scattering Technology
- Bioparticulate Monitors - Light Scattering Technology

7.3 Potentially Adaptable Technology
- Fiber Optic-Based Biosensor
- Dye-Loaded Microspheres
- Detection of ATP
- Cell-Based Biosensor
- Polymerase Chain Reaction
- Bio-Optoelectronic Sensor Systems (BOSS)
- Surface Plasmon Resonance (SPR)
- Electrochemiluminescence (ECL)

7.4 Emerging Technology
- Lateral Flow Assay
- Labels
- Magnetic Beads
- Flow-Through Columns
- Raman Spectroscopy
- Microelectrode Arrays
- Microarray of Gel-Immobilized Compounds
- Magnetic Microbeads
- DNA Microarrays
- DNA Microarrays
- DNA Microarrays

8. Conclusions & Recommendations

- Viable integrated EWSs are several years away
- Individual components
  - Some available
  - Most under development
- EWSs for water distribution systems
  - Largely theoretical
- Preliminary stages
- Utilities have not implemented software for modeling intentional contamination events
- Types of contaminants and levels of exposure have not been well defined to support selection of sensor technologies.
- Also, all of these technologies should be verified and affordable, and should operate consistently in the field.

BTO research UV probe

- Non-specific detection
- UV sensitive compounds
- Parameters
  - Turbidity
  - DOC
  - Nitrate
  - UV254
  - Organic molecules
- Drinking water µg/L
- Surface water mg/L
- Ammonium (under development)
E-nose

Vaporous compounds
Non-specific interactions
Pattern recognition
Correlation
Sensory panel
GC-MS
Training / Learning

Granulates, PCA

Granulates, SQC

Discrimination index = 68

Discrimination index = 61

Discrimination index = 50

Discrimination index = 29

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UKWIR workshop sensors
BTO research
Micro-array
- Genotoxicity detection
  - cDNA probes (10,000 genes)
  - Pattern recognition
  - Different toxicity pathways
  - Prokaryotic and Eukaryotic

Optical fibers
- Toxicity detection
  - Bacteria
    - 3D genetic modifications known
  - Fiber tip
  - Luminescence
  - Lux-gene
    - Luciferase
  - Range of chemicals
    - Benzene etc.
    - Superoxide-providing chemicals
    - DNA-damaging compounds
    - Phenols
    - Heavy metals
    - Genotoxicants
    - Estrogens

Optical Chemical Sensors (1)
- Silicon technology
- High density sensor surfaces
- Mass production
- Multiple analytes
- Internal reference
- Group specific interactions
  - Enzymes
  - Receptors
  - Proteins
  - Chemicals
- Pattern recognition
- (Bio)chemical coating developments

Optical Chemical Sensors (2)
- Water hardness
- Cations
  - K⁺
  - Na⁺
  - Ca²⁺
  - Mg²⁺
- Anions
  - HCO₃⁻
  - Cl⁻
  - SO₄²⁻
- Testing
  - Robustness
  - Reproducibility
  - Repeatability
  - On-site

Capillary electrophoreses
- Real-time on-line monitoring of contaminants in water
  - BTO 2008.028
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Non-specific
- Insecticides, 2-3 µg/L
- Organic compounds, 50 µg/L

Two effects
- Toxicological
- Physiological

Objectifying the results
- Quality guarantee of construction (ISO 15839, Water quality -- On-line sensors/analyzing equipment for water -- Specifications and performance tests)

The hydraulic model

Dosing contaminant at different locations

Conclusions modelling
- Hydraulic modelling powerful tool in understanding network
- Can be used to assess/optimise monitoring strategies
- Can be used to evaluated potential impact on public health
  - Site of introduction contaminant determines impact
  - Chemical agent can have large effect if highly toxic
  - Pathogen can have large effect even at very low CFUs
  - Dilution very important factor for chemicals, not so much for pathogens (see different impact of reservoir contaminations)
- Strategic placement of EWS is essential if detection is required in time
Running ahead into the future

- New monitoring strategies!
  - Laboratory based
  - On-line based
  - Combination
- New detection approaches!

Adapt to water utilities needs!

Booming developments needed

- What will the future technology have to look like?
  - What has to be measured?
  - Where has to be measured?
- Water quality
  - Source
  - Treatment
  - Distribution

Find the drivers

- Database
  - Questionnaire
- Workshop, Jan-Feb 2007
  - Representatives of global water works, scientists and equipment producers
  - Setting prioritization
  - Define the white gaps
  - Definition of research projects

Let’s have a talk
On-Line monitoring Selection and Installation

Wendy Smalley
Thames Water

Parameters

- Ammonia
- Hydrocarbons
- Nitrate
- Turbidity
- Dissolved oxygen
- pH
- Conductivity
- Oil on water
- Pesticides (Grimsbury only)

Monitoring site at Fobney
INSTRUMENT SELECTION
INSTALATION
Filtration
Telemetry
Waste disposal
Building Requirements
Health and safety
Types of Treatment Works

- **Surface Water**
  - Direct River Abstraction: 5 works
  - Pumped Storage Reservoirs: 7 works
  - Impounding Reservoirs: 1 work

- **Groundwater**
  - 130 works of varying complexity
    - Simple disinfection
    - Iron/Manganese removal
    - Trace Organics removal

Surface Works

- **Direct River Abstraction**
  - Intake Monitoring
    - “standard suite” Turbidity, Ammonia, Nitrates, pH, Conductivity, Dissolved Oxygen plus fish monitor

- **Pumped Storage systems**
  - River to Reservoir
    - Minimum Turbidity and Ammonia

- **Reservoir to Works**
  - Minimum Turbidity

Surface Works (Cont’d)

- **Treatment Stages**
  - Ozone-Clarification-Primary Filtration-Ozone-GAC-Disinfection

- **Minimum Standards**
  - Clarification
    - Turbidity (Individual or banks)
    - pH
    - Coagulant dose
  - Primary filtration
    - Individual turbidity
    - Headlosses
  - Secondary Ozone
    - Residual ozone
  - GAC
    - Turbidity (Individual or banks)
  - Disinfection
    - Chlorine dual validation
    - pH

Surface Works (Cont’d 2)

- **Final Water Monitoring**
  - Chlorine (dual validation)
  - Turbidity
  - pH
  - Residual Coagulant
  - Ortho Phosphate
  - Nitrates (Direct Abstraction)

Groundwater

- **Final Water (all sites)**
  - Chlorine (dual validation)
  - Turbidity
  - Nitrates (where blended or removed)
  - Fluoride (where dosed or blended)
  - Iron (where appropriate)

- **Iron/Manganese Filter Plants**
  - Individual filter turbidity (some sites by risk assessment)
Data Capture and Analysis

- Connected to Regional Telemetry System
  - Trend information
  - Alarm handling
  - Data available across the company to anyone
- More complex works have SCADA systems
- All sites have:
  - Local chart recording
  - Local manual trend review
- Data analysis
  - Real time
  - Long term trend analysis
On-line monitoring - Distribution

John Proctor
Yorkshire Water

UV 254nm

First Instrumentation

- Flow
- Pressure
- pH
- Conductivity
- Redox potential
- Turbidity
- Temperature
- Dissolved oxygen

- Water balance
- Hydraulic calibration
- Indicators of chemical change
- Readily available
- Secondary calibration

Real-time on-line monitoring of contaminants in water
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This is very heavy – a two man operation – also attenuates signals.
For Non-WTW applications

ACCESS !!!!!
No waste streams
Power
Comms
Control????
Size is important
Small – easier to get into the main
Need to look very ordinary

Closure of 36” outlet main valve

Real-time on-line monitoring of contaminants in water

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Valving Operations at Daisy Hill - Detail of Initial turns

Initial Closure Turbidity Effects

Closing of 36” outlet main valve

Calibrated CENSAR versus valve turns

Controlling Turbidity Level

Thankyou
Rapid Analytical Response in Emergency Situations

Dr David Holt, Thames Water
UKWIR Project Manager

Project Background
- Threat of malicious contamination to drinking water supplies, whether perceived or real is of concern to companies, customers, regulators and government
- UK have a long history in anticipating potential threats and developing capabilities for detecting contaminants in drinking water
- Since 9/11 UK there have been new initiatives to strengthen laboratory capability with respect to sampling and rapid analysis.

Project Management
- Contractors: Alcontrol
- UKWIR Project Client: Dr Arnold Bates, Bristol Water
- UKWIR Project Management: Dr David Holt, Thames Water
- Steering Group members: John Gray, DWI
  - Julian Dennis, Wessex Water
  - Martin Furness, Severn Trent Water

Project Objectives
- Review existing literature and ongoing studies on analytical techniques.
- Evaluate available technology for rapid screening based on rapidity, robustness, LOD, accuracy and propensity to produce false positive/negative results.
- Provide the industry with advice on rapid robust screening techniques, practical guidance and awareness.

On-site analysis
- Providing a rapid result for the absence of chemical, radiological and microbiological contamination is difficult
- Screening tests should be robust with minimal false positives or negatives
- To convincingly prove a negative in a short time, rapid screening tests are considered essential
- There is no universal toxicity monitor

Real-time on-line monitoring of contaminants in water
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On-site analysis

- The USEPA State of the Art Review: Technologies and Techniques for Early Warning Systems (EWS) to Monitor and Evaluate Drinking Water Quality gives good coverage of research on portable field test kits.
- Several test kits intended for field use have been evaluated in the UK,
  - arsenic and cyanide, cholinesterase inhibition
  - photo-ionisation detector
  - radioactivity monitor
  - pH, turbidity and conductivity
  - UV spectrophotometer
  - Non-specific toxicity testing devices using bacteriological (Deltatox) and enzyme linked (ECLOX) luminescence
- Although each of the kits had its value the overall coverage is limited compared to the laboratory
- On-site screening is only suitable for targeted analysis (i.e when the parameter being analysed for is known).
- Mobile laboratories with a whole suite of test kits and simple screening techniques are not considered to be either viable or cost-effective for low frequency emergency incident events
- Preference is to take the example to the laboratory where more extensive analytical equipment is available

Laboratory Screening

- Specific parameters
  - ICP-MS
  - State of art GC-MS (GC-TOF?)
  - LC-MS/MS or LC-TOF (no sample pre-treatment)
  - Ion chromatograph
  - Discrete analyser
  - 8 – 10 channel gross alpha/beta detection system
  - NMR (and ultimately SERS) screening for COC.
- Non-specific parameters
  - Photoionisation detector (PID)
  - UV diode array spectrometry (230 – 350 nm)
  - Cholinesterase inhibition test ticket (not immunoassay test kit)
  - Thamnocephalus platyurus inhibition (1 and 24h)
  - Microtox® 10 and 30 min
  - Total organic carbon (TOC)
  - Detergents/surface active agent tests needed
‘State of the Art’ Real-time on-line monitoring of contaminants in water

Questionnaire Responses
Dr David Holt, UKWIR Project Manager
Thames Water Research and Development

Questionnaire Aims
- To identify UK instrument needs for on-line monitoring of water quality parameters
- Part of an exercise in gathering information from users in the UK, USA and Netherlands
- To provide a basis for the UKWIR project ‘Risk Studies and intake protection’

Feedback Received – To date
- 8 Companies have provided feedback
- Large and smaller companies responded
- Responses collated into determinants for:
  - On-Line instruments
  - Laboratory or on-site analysis

On-line Instrumentation (1)

<table>
<thead>
<tr>
<th>Parameter measured</th>
<th>Stored Water</th>
<th>Ground Water</th>
<th>Surface Water</th>
<th>Treatment</th>
<th>Final Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Pressure</td>
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<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Temperature</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Conductivity</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>pH</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>DOC/TOC</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Chlorine</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Spectral</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Titratable X</td>
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<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Particle count</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Oil on water</td>
<td>X</td>
<td>X</td>
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On-line Instrumentation (2)

<table>
<thead>
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<th>Surface Water</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Manganese</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Fluoride</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Sodium</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Aluminum</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Nitrate</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Orthophosphate</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Ammonium</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Carbonate</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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Laboratory testing (1) - Taste and colour

<table>
<thead>
<tr>
<th>Parameter measured</th>
<th>Stored Water</th>
<th>Ground Water</th>
<th>Surface Water</th>
<th>Treatment</th>
<th>Final Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Odour</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Taste</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Geosmin &amp; MIB</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Micocystin</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Colour</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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</table>
### Laboratory testing (2) - Inorganics

<table>
<thead>
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<th>Stored</th>
<th>Ground water</th>
<th>Surface water</th>
<th>Treatment</th>
<th>Final water</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chloride</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfate</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrate</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bicarbonate</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Hardness</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Redox Potential</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrite</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
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</table>

### Laboratory testing (3) - Metals

<table>
<thead>
<tr>
<th>Parameter measured</th>
<th>Stored</th>
<th>Ground water</th>
<th>Surface water</th>
<th>Treatment</th>
<th>Final water</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cyanide</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mercury</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
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<tr>
<td>Chromium</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
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<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zinc</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cadmium</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
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### Laboratory testing (4) – Biological Parameters

<table>
<thead>
<tr>
<th>Parameter measured</th>
<th>Stored</th>
<th>Ground water</th>
<th>Surface water</th>
<th>Treatment</th>
<th>Final water</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algae</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E coli</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coliforms</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clostridium</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enterococcus</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P. aeruginosa</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate counts</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cryptosporidium</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Giardia</td>
<td>X</td>
<td>X</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
II. Pre-workshop AwwaRF, February 27, 2007

a. Summary

AwwaRF and Kiwa Water Research organised a workshop held in Dallas (Texas USA) on the 27th of February 2007 for AwwaRF subscribers on ‘on-line monitoring of contaminants in water’. The objective of the workshop was to discuss US utility experiences and needs on on-line monitoring.

A group of 16 representatives of US water works attended the workshop and engaged in fruitful discussions.

Presentations
After an introductory presentation by Hsiao-Wen Chen (AwwaRF) and Theo van den Hoven (Kiwa Water Research) on the scope of the project, Bram van der Gaag (Kiwa Water Research) presented the current state of sensor technology. Subsequently water quality experts from US utilities presented their experiences and needs regarding on-line monitoring systems for different application. Stanley States (Pittsburgh Water and Sewer Authority) reported on on-line monitoring for drinking water security, Bruce Johnson (Tucson Water) on on-line monitoring to inform the community and enhance their involvement and Zia Bukhari (American Water) on monitoring to improve distribution system operations.

Discussions
During discussion the following conclusions were made.
- On-line monitoring systems should serve multiple benefits, sensors just for security will not survive
- We should make better use of available technology, instead of waiting for the ‘holy grail’
- Current systems need a lot of maintenance, it is not just plug and play
- Current verification schemes do not sufficiently cover utility needs
- Smart data collection and interpretation is crucial. Understand the data that you collect
- Regulators should be involved.
### b. Agenda

**Tuesday, February 27, 2007**

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:30 a.m.</td>
<td>Continental breakfast</td>
</tr>
<tr>
<td>9:30 a.m.</td>
<td>Introduction to workshop and link to AwwaRF research program (AwwaRF)</td>
</tr>
<tr>
<td>9:45 a.m.</td>
<td>Scope, objectives, and setup of the workshop (KWR)</td>
</tr>
<tr>
<td>10:00 a.m.</td>
<td>Collaborative project (KWR)</td>
</tr>
<tr>
<td>10:30 a.m.</td>
<td>Break</td>
</tr>
<tr>
<td>10:45 a.m.</td>
<td>Online Monitoring for Drinking Water Security (Dr. Stanley States, Pittsburgh Water and Sewer Authority)</td>
</tr>
<tr>
<td>11:05 a.m.</td>
<td>Environmental Monitoring for Public Access and Community Tracking (Mr. Bruce Johnson, Tucson Water)</td>
</tr>
<tr>
<td>11:45 a.m.</td>
<td>Results of the US and European utility surveys on online monitoring (KWR)</td>
</tr>
<tr>
<td>Noon</td>
<td>Lunch</td>
</tr>
<tr>
<td>1:15 p.m.</td>
<td>Open discussion: Needs of AwwaRF subscribers (all workshop participants)</td>
</tr>
<tr>
<td>3:00 p.m.</td>
<td>Break</td>
</tr>
<tr>
<td>3:15 p.m.</td>
<td>Follow up (KWR)</td>
</tr>
<tr>
<td>3:45 p.m.</td>
<td>Synthesis and conclusions (AwwaRF &amp; KWR)</td>
</tr>
<tr>
<td>4:00 p.m.</td>
<td>Close of meeting</td>
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</table>
## c. List of participants

Attendees of the US workshop “State of the art of real-time online monitoring of contaminants in water”

<table>
<thead>
<tr>
<th>Name</th>
<th>Position</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cynthia Andrews-Tate</td>
<td>Laboratory Services Supervisor</td>
<td>Long Beach Water Department</td>
</tr>
<tr>
<td>Zia Bukhari</td>
<td>Senior Environmental Scientist</td>
<td>American Water</td>
</tr>
<tr>
<td>Jane F. Byrne</td>
<td>Director of Water Treatment</td>
<td>Hanahan Water Treatment Plant, Charleston Water System</td>
</tr>
<tr>
<td>Rick Dalton</td>
<td>Director of Engineering</td>
<td>Park Water Company</td>
</tr>
<tr>
<td>Monica Hoyt</td>
<td>Laboratory Director</td>
<td>Central Utah Water Conservancy District</td>
</tr>
<tr>
<td>Ronald Hunsinger</td>
<td>Manager of Water Quality</td>
<td>East Bay Municipal Utility District</td>
</tr>
<tr>
<td>Bruce Johnson</td>
<td>Deputy Director</td>
<td>Tucson Water</td>
</tr>
<tr>
<td>Dave Johnson</td>
<td>Treatment Manager</td>
<td>Southern Nevada Water System</td>
</tr>
<tr>
<td>Marcis Kempe</td>
<td>Director, Operations Support</td>
<td>Massachusetts Water Resources Authority</td>
</tr>
<tr>
<td>Bart Koch</td>
<td>Water Quality Laboratory Manager</td>
<td>Metropolitan Water District of Southern California</td>
</tr>
<tr>
<td>Yves B. Mikol</td>
<td>Director</td>
<td>New York City Department of Environ Protection</td>
</tr>
<tr>
<td>Christine Owen</td>
<td>Water Quality Assurance Officer</td>
<td>Tampa Bay Water</td>
</tr>
<tr>
<td>Pankaj Parekh</td>
<td>Director-Water Quality Compliance</td>
<td>Los Angeles Dept of Water and Power</td>
</tr>
<tr>
<td>Ralph Rogers</td>
<td>Senior Research Engineer</td>
<td>Philadelphia Water Department</td>
</tr>
<tr>
<td>Stanley States</td>
<td>Water Quality Manager</td>
<td>Pittsburgh Water and Sewer Authority</td>
</tr>
<tr>
<td>Jeffrey Swertfeger</td>
<td>Supervising Chemist</td>
<td>Great Cincinnati Water Works</td>
</tr>
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### Project Personnel

<table>
<thead>
<tr>
<th>Name</th>
<th>Position</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theo van den Hoven</td>
<td>Manager Research Programme</td>
<td>Kiwa Water Research</td>
</tr>
<tr>
<td>Bram van der Gaag</td>
<td>Scientific Researcher “Monitoring and Sensing”</td>
<td>Kiwa Water Research</td>
</tr>
<tr>
<td>Hsiao-wen Chen</td>
<td>Project Manager</td>
<td>Awwa Research Foundation</td>
</tr>
<tr>
<td>AwwaRF Staff</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frank Blaha</td>
<td>Senior Project Manager</td>
<td>Awwa Research Foundation</td>
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</table>
d. Presentations
State of the Art of Real-Time Online Monitoring of Contaminants in Water

US Workshop
Dallas, Texas
February 27, 2007

Hsiao-wen Chen
Awwa Research Foundation

Agenda
- List of participants
- Introduction
- Security: Presentation by Stanley States
- Public Access: Presentation by Bruce Johnson
- Distribution: Presentation by Zia Bukhari
- Expense report form

Notebook

AwwaRF Research Programs
- Solicited
- Unsolicited
- Tailored Collaboration
- Partnership

AwwaRF Project 4025
- State of the art of online monitoring of contaminants in water
- Partnership project with Kiwa
- Kiwa Research Program Manager: Dr. Theo van den Hoven
- Project Managers
  - Kiwa: Bram van der Gaag
  - AwwaRF: Hsiao-wen Chen

What is AwwaRF
- Awwa Research Foundation
- Member-supported
- International
- Nonprofit
- Sponsors research to enable water utilities, public health agencies, and other professionals to provide safe and affordable drinking water to consumers.

AwwaRF Project 4025
- Objectives
  - Investigate and prioritize water utilities needs
  - Develop research roadmap
- Scope
  - Surveys
  - Local workshops
  - International workshop
  - Roadmap
AwwaRF Project 4025

- Schedule
  - US workshop: February 27 2007
  - International workshop: March 22-23, 2007
  - Interim report: April 2007
  - Final report: September 2007
  - Final report publication: March 2008

Agenda (afternoon)

- 01:15 Open discussion (all)
- 03:00 Break
- 03:15 Follow up (Kiwa)
- 03:45 Synthesis and conclusions (Kiwa & AwwaRF)
- 04:00 Have a nice trip back home

Agenda (morning)

- 09:30 Introduction (AwwaRF)
- 09:45 Workshop scope, objectives, and setup (Kiwa)
- 10:00 Global Water Research Coalition project (Kiwa)
- 10:45 Presentation #1 Security (Stanley States)
- 11:05 Presentation #2 Public access & community tracking (Bruce Johnson)
- 11:25 Presentation #3 Distribution system (Zia Bukhari)
- 11:45 US & European survey results (Kiwa)

Thank you!

Hsiao-wen Chen
hchen@awwarf.org
Awwa Research Foundation
http://www.awwarf.org

Real-time on-line monitoring of contaminants in water
BTO 2008.028
© Kiwa Water Research - 96 -
May 16, 2008
Scope, objectives and set up of the workshop

AwwaRF, Dallas
February 27th, 2007

Theo van den Hoven

Safety by risk management

Analysing and minimising risks for water quality and public health

Know your catchment
Know your raw water
Know your treatment
Safeguard the distribution system
Safeguard the household plumbing
Safe drinking water

On-line water quality monitoring can assist .... Quality control before water is consumed

Sensors and Early Warning Systemen

Intake protection
Process Control
Terror

Sensor for treatment performance

Real-time on-line monitoring of contaminants in water
Booming developments, lots of promises but what is reality?

Current situation:
- periodical samples + laboratory analyses
- use of sensors for limited number of parameters
- requirements of users often not met with available systems

Advances in technology (ICT, microelectronics, a.o.)
new and significantly enhanced sensor capabilities
on-line monitoring water quality real possibility

UKWIR, AwwaRF, Kiwa Water Research and other GWRC partners have expressed the desire to explore opportunities

Joining forces
Global Water Research Coalition

Monitoring, sensor and communication technology identified as key issue by WSSTP

WSSTP delivers
- Vision
- Research Agenda
- Implementation Plan
for European Water Sector
(www.wsstp.org)

The project
Understand and utilise opportunities

- Partners: UKWIR, AwwaRF and Kiwa Water Research
- Undertake review of what analysis is needed
  - UK workshop
  - NI inventory
  - US workshop
  - GWRC questionnaire
- Determine
  - what is available
  - what needs development.
- Present results in international seminar
  - 22, 23 March 2007
  - Kiwa Water Research (NI)

Today

- Inventorise AwwaRF member needs and experiences
- Present project results until now
- Identify opportunities
First results of the GWRC collaborative project

AwwaRF, Dallas, Texas, USA
February 27th, 2007

Monitoring, Definition

Any kind of acquisition or collection of data on a certain state, activity or process by means of a technical device, an observation system or any other surveying method to assess the current status of the chosen parameters and changes over time.

Monitoring issues

- Data
  - Type of data needed
- Technical device
  - Laboratory equipment
  - Sensors, detectors
- Current states
  - Real-time
  - Near real-time
  - 24 hours
  - Week
- Changes over time
  - Access to historical data

Present situation

- Laboratory measurements
  - Chemical analyses
    - Anorganic: HPLC-MS, GC-MS, ICP-MS, etc.
    - Organic: HPLC-MS, GC-MS, ICP-MS, etc.
  - Microbiological
    - Total count, Gram staining, Classical and Molecular Identification etc.
- On-line Real-time
  - pH, Conductivity, O₂, TOC (total organic compounds), DOC (dissolved organic compounds), UV, Temperature, Pressure, Turbidity etc.

Present situation satisfactory?

- Consumers safety?
- Optimized process?
  - Overkill or cost effective
- New technologies under development

EPA technology survey EWS

EPA Report
December 2005
6. Technologies that Detect Chemical Contaminants for Early Warning Systems

6.2 Available Technology
6.2.1 Detection of Arsenic
6.2.2 Detection of Cyanide
6.2.3 Gas Chromatography
6.2.4 Enzyme-Based Detection
6.2.5 Biosensors

6.3 Potentially Adaptable Technology
6.3.1 Enzyme-Based Detection
6.3.2 Organism-Based Biosensors
6.3.3 Infrared Spectroscopy
6.3.4 X-ray Fluorescence
6.3.5 Ion Mobility Spectroscopy
6.3.6 Microchips for Portable Chemical Sensors
6.3.7 Microchip Surface Acoustic Wave (SAW) Technology
6.3.8 MicrochipChemiresistors

6.4 Emerging Technology
6.4.1 Organism-Based Biosensors
6.4.2 Eukaryotic Cell-Based Biosensors
6.4.3 Fiber Optic Cable-Based Sensors
6.4.4 Cell-Based Biosensor
6.4.5 Polymerase Chain Reaction
6.4.6 Bio-Optoelectronic Sensor Systems (BOSS)
6.4.7 Surface Plasmon Resonance (SPR)
6.4.8 Electrochemiluminescence (ECL)

7. Technologies that Detect Microbial Contaminants for Early Warning Systems

7.2 Available Technologies
7.2.1 Immunoassays
7.2.2 Detection of ATP
7.2.3 Flow Cytometry- and Micro-Flow-Based Technology
7.2.4 Bioparticulate Monitors - Light Scattering Technology

7.3 Potentially Adaptable Technology
7.3.1 Fiber Optic-Based Biosensor
7.3.2 Dye-Loaded Microspheres
7.3.3 Detection of ATP
7.3.4 Cell-Based Biosensor
7.3.5 Eukaryotic Cell-Based Biosensor
7.3.6 Polymerase Chain Reaction
7.3.7 Microarray of Gel-Immobilized Compounds
7.3.8 Magnetic Microbeads
7.3.9 DNA Microarrays

7.4 Emerging Technology
7.4.1 Lateral Flow Assay
7.4.2 Labels
7.4.3 Magnetic Beads
7.4.4 Flow-Through Columns
7.4.5 Raman Spectroscopy
7.4.6 Microelectrode Arrays
7.4.7 Magnetic Microbeads
7.4.8 DNA Microarrays

Conclusions & Recommendations

- Viable integrated EWSs are several years away
- Individual components
  - Some available
  - Most under development
  - Not tested or verified
- EWSs for water distribution systems
  - Largely theoretical
  - Preliminary stages
- Utilities have not implemented software for modeling intentional contamination events
- Types of contaminants and levels of exposure have not been well defined to support selection of sensor technologies.
- Also, all of these technologies should be verified and affordable, and should operate consistently in the field.

Real-time on-line monitoring of contaminants in water

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BTO 2008.028
May 16, 2008
**BTO research / AwwaRF UV-probe**

- UV-probe measurements
- Absorbance vs. Wavelength

**BTO research / AwwaRF UV probe measurements**

- Graph showing absorbance vs. Wavelength

**BTO research / AwwaRF E-nose**

- Vaporous compounds
- Non-specific interactions
- Pattern recognition
- Correlation
- Sensory panel
- GC-MS
- Training / Learning

**BTO research / AwwaRF E-nose, Equipment setup**

- Diagram of E-nose setup
- Metal oxide sensor chamber
- Chamber A (CL2)
- LY2 sensors
- Mass Flow Meter
- Headspace
- Exhaust

**BTO research / AwwaRF E-nose, Odour & Flavour panel**

- Migration experiments
  - 1st, 2nd and 3rd migration
  - Each 72 hours
  - Use of tap water
- Panel
  - 8 individuals
  - Figures between 0 and 10

**BTO research / AwwaRF E-nose, Samples**

- Migration experiments
  - 1st, 2nd and 3rd migration
  - Each 72 hours
- Polymers & Rubbers
  - PVC
  - PE
  - NBR
  - EPDM
- Blind testing
  - E-nose
  - GC-ToF-MS
- No sample pretreatment and concentration

---

Real-time on-line monitoring of contaminants in water
May 16, 2008
**AwwaRF workshop sensors**

**BTO research**

Optical fibers

- Toxicity detection
  - Bacteria
  - 3D genetic modifications
  - Luminescence
- Fiber tip
- Lux-gene
- Luciferase
- Range of chemicals
  - Benzene etc.
  - Superoxide providing chemicals
  - DNA-damaging compounds
  - Phenols
  - Heavy metals
  - Genotoxicants
  - Estrogens

**BTO research / AwwaRF (1)**

Silicon technology
- High density sensor surfaces
- Mass production
- Multiple analytes
- Internal reference
- Group specific interactions
- Enzymes
- Receptors
- Proteins
- Chemicals
- Pattern recognition
- (Bio)chemical coating developments

**BTO research / AwwaRF (2)**

Direct detection of 5 µg/L Atrazine

**BTO research (2004)**

Capillary electrophoreses

- Water hardness
- Cations
  - K⁺
  - Na⁺
  - Ca²⁺
  - Mg²⁺
- Anions
  - HCO₃⁻
  - Cl⁻
  - SO₄²⁻
- Testing
  - Robustness
  - Reproducibility
  - Repeatability
  - On-site

**BTO research (Lionix 2005)**

Capillary electrophoreses

- Full serum
  - EC-min (m V)
  - Time (s)
BTO research (2006)
Capillary electrophoreses, before softening

Capillary electrophoreses, after softening

Inter chip robustness
- pH
- Composition
- Buffer choice
Reproducibility
Repeatability
Use of different water samples

Non-specific
- Insecticides, 2-3 µg/L
- Organic compounds, 50 µg/L

Two effects
- Toxicological
- Physiological

Objectifying the results

Quality guarantee of construction (ISO 15839, Water quality -- On-line sensors/analysing equipment for water -- Specifications and performance tests)

Real-time on-line monitoring of contaminants in water

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BTO 2008.028
May 16, 2008
Hydraulic modelling powerful tool in understanding network
Can be used to assess/optimise monitoring strategies
Can be used to evaluated potential impact on public health
- Site of introduction contaminant determines impact
- Chemical agent can have large effect if highly toxic
- Pathogen can have large effect even at very low CFU/L
- Dilution very important factor for chemicals, not so much for pathogens (see different impact of reservoir contaminations)
- Strategic placement of EWS is essential if detection is required in time

Running ahead into the future
- New monitoring strategies!
  - Laboratory based
  - On-line based
  - Combination
- New detection approaches!

Adapt to water utilities needs!

Booming developments needed
- What will the future technology have to look like?
  - What has to be measured?
  - Where has to be measured?
- Water quality
  - Source
  - Treatment
  - Distribution
Find the drivers

- Database
- Questionnaire
- Workshop, March 22-23, 2007
  - Representatives of global water works, scientists and equipment producers
  - Setting prioritization
  - Define the white gaps
  - Definition of research projects

Let’s have a talk
Online Monitoring for Drinking Water Security

Stanley States
Water Quality Manager
Pittsburgh Water and Sewer Authority

AWWARF Workshop: "State of the art Real-Time Online Monitoring of Contaminants in Water"
Dallas, Texas – February 27, 2007

The ability to provide security and respond to incidents (accidental or intentional) is enhanced by the ability to detect, identify, and quantify contaminants:
- Continuous online monitoring (CWS)
- Rapid sample analysis (in the field)
- Definitive sample analysis (in the lab)

Five approaches to continuous online monitoring for security purposes:
1) Monitoring routine chemical parameters as surrogates for chem, and perhaps bio, contaminants (Change of State)
2) Real-Time Toxicity Monitoring (Biosensors)
3) Monitor for radiation to detect presence of radionuclides
4) Detect, identify, and quantitate specific chemical contaminants
5) Detect, identify, and quantify specific pathogens

1) Screening for Chemical Surrogates

Utilize standard water quality parameters and “off-the-shelf” sensors
- Cl₂
- TOC
- pH
- Specific conductance
- ORP
- Chloride
- Ammonia
- Nitrate
- Turbidity
- Temperature
- DO

Several studies have shown that changes in routine chem parameters are good indicators for contaminants:
- Buyers and Carlson (2005)

*Concluded that TOC and Cl₂ are the most sensitive indicators
Screening for surrogates parameters is based on measurement of individual parameters or combinations of parameters.

- **Hach Cl-17 Chlorine Analyzer**
- **SIEVERS 900 TOC Analyzer**
- **Online Fluorometry**
  Detects aromatic hydrocarbons by measuring fluorescence in flowing stream of water:
  - BTEX
  - Gasoline
  - Aromatic solvents
  - Diesel
  - Crude oil
  Commercially available – Turner 4100 Fluorometer
- **YSI 6600 Multi-Parameter Probe**
- **Hach Event Sensor with Agent Library**
2) Real-Time Toxicity Monitoring (Biosensors)

Online Biosensors -
- Measure changes in physiology or behavior of living organisms resulting from stress induced by toxins
- Canary in coal mine
- Suggest something unusual is in water
- Cannot identify toxin

Types of Biosensors commercially available:
- Bacterial Monitoring System
- Algae Toximeter
- Daphnia Toximeter
- Mussel Monitor
- Fish Sentinel System

Fish Sentinel Systems
Avoidance behavior
Changes in swimming behavior or ventilatory patterns
- IABS – Intelligent Aquatic Biomonitoring System (Intelligent Automation Corp.)
- Medaka Sensor (Seiko Corp.)
- Bio – Sensor Series 7000 (Biological Monitor Inc.)
3) Online Monitoring for Radiation

Measure nonspecific radiation in water (alpha, beta, gamma)

Commercially available sensors:
- Technical Associates Inc. SSS-33-5FT (Continuous flow-through scintillation detection of alpha, beta, and gamma)
- Canberra Inc. OLM 100 (Continuous measurement of gamma)

4) Online Detection, Identification, and Quantitation of Specific Chemical Contaminants

Some commercially available Instruments:
- Online gas chromatography (GC) Inficon Scentograph CMS 200, CMS 500
- Online Gas Chromatography – Mass Spectrometry (GC-MS) HAPSITE / Source Sentinel
5) Online Detection, Identification, and Quantification of Specific Pathogens

Unique light scattering patterns of organisms enable creation of ‘Bio-Optical Signatures’ to classify the pathogen.
Conclusions concerning online monitoring capabilities for security purposes:

- Analytical capabilities are still limited
- Must use currently available technologies
- Must communicate to Decision Makers and Incident Commanders the limitations of data produced by these technologies

Conclusions (cont)

- Measurement of physical chemical, biological and radiological parameters is only part of a comprehensive security monitoring system.

Other components:
- Routine water quality analysis
- Security information (police, utility workers)
- Intelligence info (ISAC, INFRAGARD)
- Customer complaints
- Syndromic surveillance systems

Conclusions (cont)

- Should try to obtain multiple benefits from online monitoring system
Environmental Monitoring for Public Access and Community Tracking

Providing Timely Water Quality Information to the Community

Bruce Johnson

Tucson Water is a department of the City of Tucson which operates as a public utility serving approximately 720,000 people.

• Increased water quality monitoring with a continuous online monitoring system
• Improved time relevancy of public access to water quality data
• Improve community tracking of water quality measurements through tailored reporting of individualized water quality data
• Primary interest to improve water quality awareness in the community

United States EPA Sponsors EMPACT

“Providing the Public with Timely Water Quality Information”

What’s the Quality of Our Drinking Water?

And Why is it Important to You?

Community Partnerships
**What is Tucson’s Water Quality?**

- **22 On-line Water Quality Monitoring Stations**

**Water Quality Parameters**

- **Real Time Online Measurements**
  - Chlorine
  - pH
  - Electroconductibility - Total Dissolved Solids
  - Temperature

- **Snap Shot Laboratory Measuremets**
  - Coliform
  - Hardness
  - Nitrate
  - Sodium
  - Total Trihalomethanes - THMs
  - Fluoride

**Water Quality Monitoring Points**

- **HACH Monitoring System**

**Most Recent Water Quality Measurements at EMPACT Monitoring Station 1**

- Delivering up-to-date water quality information on the web from over 400 sampling locations
Benefits

- Able to detect water quality changes in real time
- Able to review multiple data sets at one time
- A real time view of the potable system
- Readily see a trend
- Able to integrate data from physical locations using a web based GIS application
- Quick data retrieval to make timely decisions
- Able to add new parameters as technology improves
- Multiple uses

Building our Security Future

- Testing & Evaluating New Technologies
- Building on the EMPACT framework
  - Controlled environment
    - Challenge testing to determine analytical capabilities
  - Distribution System Challenges
    - Operational
    - Technological
    - Environmental
Enhanced Monitoring in Distribution Systems

Zia Bukhari, Ph.D.
Senior Environmental Scientist

Water Security?
Last 5 years... some progress, but is it enough?
- Equipment expensive and reliability questionable
- Most utilities uncertain how to deploy monitors & respond to alarms
- What constitutes an alarm?
- Various guidelines but no regulatory drivers

Every year decreasing concern for Water Security issues
Is this OK? Is the cost not justified? Can enhanced monitoring offer other benefits?

Intrusion control
- Aging distribution system infrastructure poses economic (non-revenue water) and WQ (cross connections) challenges
  - Potential for accidental intrusion
- Backpressure
  - the flow from a customer’s pressurized system through an unprotected cross-connection back into the potable water supply
- Backsiphonage
  - backflow resulting from a negative or reduced pressure in the water distribution supply

Sources of Pressure Transients
- Service interruptions
  - Power failure
  - Main breaks
- Distribution system operation
  - Pump startup and shut down
  - Valve operation
  - Feed tank draining
  - Surge tank draining
  - Resonance
- Sudden change in demand
  - Flushing operations
  - Opening and closing a fire hydrant

Power Outage
- Transient follows a power outage at a pumping station
Overall 56% (18/32) of samples were positive for viruses: enteroviruses (Sabin strain), Norwalk, and Hepatitis A virus.

Monitoring Intrusion

- Fixed-based acoustic monitor constantly listens for leaks
- Low-cost, waterproof sensor installed near a water meter
- Easily strapped to service pipe
- Anticipated range +/- 500 feet
- Maintenance-free, 10+ years (battery)
- Mobile radio or fixed-network AMR communication interface

Backflow Detection

- Cost Effective Meter Reading
  - Efficient collection of meter reads
  - Improved customer service
  - Resolve billing issues
  - Identify service line leaks
  - Reduced read-related injuries
- Identify & Control Leakage
  - Reduced Non-Revenue Water
  - Limit opportunities for intrusion
- Improved Security
  - Detection of Cross Connection and Backflow events
  - Detection of intentional contamination events

Intrusion Control

Backflow & Backsiphonage may be naturally occurring or intentional phenomena:

- What are the WQ impacts of such events?
- How do we detect them in a timely manner to minimize their impact?
On-line monitoring

- Should provide broad coverage for various contaminants
- Costs necessitate strategic location of sensors
- Optimal, spatial or vulnerable sites
- Data management
- Integration with other technologies to assist routine operations

Surrogates for Measuring Water Quality

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissolved oxygen (DO)</td>
<td>Indicator of potential biological activity. Low levels yield anoxic conditions &amp; release of dissolved metals (iron, manganese)</td>
</tr>
<tr>
<td>Oxidation-reduction potential (ORP)</td>
<td>Indicator of dissolved oxidizing and reducing agents (metal ions, chlorine, ozone, sulfite ion). ORP values &gt; 650 mV indicate disinfection. BOD and ammonia lower ORP by increasing chlorine demand</td>
</tr>
<tr>
<td>Total or Free Chlorine</td>
<td>Chlorine demand, mostly from nitrogen and organic compounds</td>
</tr>
<tr>
<td>Temperature</td>
<td>Indicator of hydrogen ion activity (acidity or alkalinity) of water. Most chemical (e.g. corrosion) and biochemical processes (e.g. disinfection) are pH dependent</td>
</tr>
<tr>
<td>pH</td>
<td>Indicates hydrogen ion activity (acidity or alkalinity) of water. Must chemical (e.g. corrosion) and biochemical processes (e.g. disinfection) are pH dependent</td>
</tr>
<tr>
<td>Turbidity</td>
<td>Gross measurement of particulates. Reduces disinfection efficacy &amp; may indicate microbial presence</td>
</tr>
<tr>
<td>pH</td>
<td>Temperature alone not an indicator of contamination. However, biological &amp; chemical activities influenced by water temp. DO and conductivity also affected</td>
</tr>
<tr>
<td>pH</td>
<td>A gross indicator of organic matter. Does not provide characterization. Analytical methods require reagents</td>
</tr>
<tr>
<td>Ultraviolet Absorbance /Transmittance (UV)</td>
<td>Gross indicators of organic matter. Optical rather than chemical methods for TOC</td>
</tr>
<tr>
<td>Total Organic Carbon (TOC)</td>
<td>A gross indicator of organic matter. Does not provide characterization. Analytical methods require reagents</td>
</tr>
</tbody>
</table>

Sensor Reliability

- Uncorrected
- Corrected (5%-25%)
- Deleted (>25%)

Sensor Locations

Primary objective to provide timely notification of unexpected changes in water quality

Ideally sensors would be located at each service connection with real time and automated feedback:

- Operational changes (i.e. increased chlorine injection)
- Substitute or divert supply when WQ conditions exceed predefined specifications

Placement may be influenced by objectives:

- For operational optimization, installations downstream of vulnerable sites may be most prudent
- EWS may require better spatial distribution to capture customer density
Online WQ information to meet regulatory goals

Total Coliform rule: minimize fecal pathogens: minimize public notifications, improve customer perception

LT2 ESTWR: minimize Cryptosporidium exposure

DBPR: minimize exposure to potentially carcinogenic DBPs

Lead and Copper Rule: reduction of corrosivity to minimize exposure to L&C

May help to improve localized flushing, valve op and tank turnover practices

Disinfection Control

Chlorination

Can yield halogenated DBPs. >500 DBPs may have health effects.

- Chlorine optimization to control regulated/unregulated DBPs
- Better control of coliforms and reduction of microbial re-growth

Chloramination

Nitrification yields increased nitrite/nitrates. Alkalinity, pH, DO and disinfection residuals also impacted. Potential for bacterial re-growth.

- Better control of TOC, ammonia and pH beneficial

Potential benefits for existing Regs: TC, DBPR

Corrosion Control

Important to minimize health impacts of lead and copper & to maintain WQ aesthetics

- pH, alkalinity, calcium hardness, phosphate, chlorine/ORP, chloride, sulfate, temperature

With these parameters can calculate various corrosion indices including:

- Langier Saturation Index (LSI)
- Calcium Carbonate Precipitation Potential (CCPP)
- Larson Ratio (LR)

Potential benefits for existing Regs: TC, LCR

Protecting Integrity of DW

Approach:

- Online WQ sensors strategically located to measure anomalies (say 100 miles)
- Interspersed with spatially distributed pressure & acoustic monitors (say 50 miles)
- Data management software for timely notification

Data Transmission using Radio Communications

- Real-time on-line monitoring of contaminants in water BTO 2008.028

Integration of online monitors into routine operations
Recap

What we understand now:
- Useful contaminant monitoring, Installation & maintenance costs and potential benefits of deployment
- How to achieve real time access to WQ data

Adequate for establishing WQ baselines, operational optimization and event verification

What we need to understand:
- Real time data management for specific anomaly characterization & EWS
- Improved prediction of fate/transport using models
- Integration of multi-streams of information to enhance Decision process
- What may be barriers to implementation?

Acknowledgements

This work is a result of a collaborative effort between American Water, US Environmental Protection Agency and the US Geological Survey. Ron Baker, Rachel Esralew and Eric Vowinkel from the USGS are thanked for sensor maintenance/data collection. Pressure management data were collected for an AwwaRF study (3008), being conducted by Kala Fleming from AWW.

Contact Information

Zia Bukhari, Ph.D.
Sr. Environmental Scientist
Research & Environmental Stewardship
American Water
1025 Laurel Oak Road
Voorhees, NJ 08043 USA
phone: (856) 309-4554
fax: (856) 782-3603
e-mail: zbukhari@amwater.com

Operational Perspective

Managerial Perspective
**Questionnaire Aims**

- To identify US instrument use for on-line monitoring of water quality parameters
- Part of an exercise in gathering information from users in the UK, USA, Belgium and Netherlands
- To provide a basis for the GWRC project “State-of-the-Art Real-time on-line monitoring of contaminants in water”

**Feedback Received – To date**

- **US**
  - 52 of 250 companies
  - 21%
- **UK**
  - 8 of x companies
  - ?
- **NL**
  - 10 of 12 companies
  - 83%

**The questionnaire**

- **Water types**
  - Stored raw water
  - Ground water
  - Surface water
  - Treatment, in process
  - Treatment, final water
  - Distribution system
  - 73 parameters

**Number of monitored “water types”**

- Stored raw water
- Ground water
- Surface water
- Treatment, in process
- Treatment, final water
- Distribution system

- 4 types 29%
- 5 types 36%
- 6 types 23%

**Source waters**

- SW = Surface water
- GW = Ground water
- RW = Stored raw water

- SW+GW 19%
- SW+RW 21%
- SW only 25%
- SW+GW only 12%

---

Real-time on-line monitoring of contaminants in water

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BTO 2008.028

May 16, 2008
On-line monitored parameters

**US**

<table>
<thead>
<tr>
<th>Parameter monitored on-line</th>
<th>Number of utilities</th>
<th>Number of sites</th>
<th>Equipment reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water flow rate</td>
<td>52 (100%)</td>
<td></td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Poor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Not specified</td>
</tr>
<tr>
<td>Turbidity</td>
<td></td>
<td></td>
<td>180 (74.7%)</td>
</tr>
<tr>
<td>pH</td>
<td>41 (79.2%)</td>
<td></td>
<td>Good</td>
</tr>
<tr>
<td>Water temperature</td>
<td>52 (100%)</td>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>Conductivity</td>
<td>20 (38.5%)</td>
<td></td>
<td>Poor</td>
</tr>
<tr>
<td>Particle count</td>
<td>19 (36.5%)</td>
<td></td>
<td>Not specified</td>
</tr>
<tr>
<td>Fluoride</td>
<td>11 (21.2%)</td>
<td></td>
<td>Good</td>
</tr>
<tr>
<td>Oxygen</td>
<td>9 (17.3%)</td>
<td></td>
<td>Poor</td>
</tr>
<tr>
<td>Ammonium</td>
<td>3 (5.8%)</td>
<td></td>
<td>Not specified</td>
</tr>
<tr>
<td>Nitrate</td>
<td>2 (3.8%)</td>
<td></td>
<td>Good</td>
</tr>
<tr>
<td>Chloride</td>
<td>1 (1.9%)</td>
<td></td>
<td>Poor</td>
</tr>
<tr>
<td>TOC</td>
<td>7 (13.5%)</td>
<td></td>
<td>Not specified</td>
</tr>
<tr>
<td>Spectral absorption/UV 254 nm</td>
<td>6 (11.5%)</td>
<td></td>
<td>Good</td>
</tr>
<tr>
<td>Algae/chlorophyll</td>
<td>3 (5.8%)</td>
<td></td>
<td>Poor</td>
</tr>
<tr>
<td>Ammonium</td>
<td>3 (5.8%)</td>
<td></td>
<td>Not specified</td>
</tr>
<tr>
<td>Nitrate</td>
<td>2 (3.8%)</td>
<td></td>
<td>Good</td>
</tr>
<tr>
<td>Chloride</td>
<td>1 (1.9%)</td>
<td></td>
<td>Poor</td>
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<tr>
<td>VOCs [FID detector]</td>
<td>1 (1.9%)</td>
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<td>Not specified</td>
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<td>Chloramine</td>
<td>1 (1.9%)</td>
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<td>Poor</td>
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<tr>
<td>DOC</td>
<td>1 (1.9%)</td>
<td></td>
<td>Not specified</td>
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<tr>
<td>Redox potential</td>
<td>1 (1.9%)</td>
<td></td>
<td>Poor</td>
</tr>
</tbody>
</table>

Comparison US-UK-NL

<table>
<thead>
<tr>
<th>Parameter monitored on-line</th>
<th>US</th>
<th>UK</th>
<th>NL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water flow rate</td>
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<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Turbidity</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>pH</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Water temperature</td>
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<td>x</td>
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<td>Conductivity</td>
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<td>Particle count</td>
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<td>Fluoride</td>
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<td>x</td>
<td>x</td>
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</tr>
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<td>Ammonium</td>
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Real-time on-line monitoring of contaminants in water

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BTO 2008.028

May 16, 2008
III. Research strategy workshop, March 22-23, 2007

a. Summary

Date: 22-23 March 2007
Venue: Kiwa Water Research, Nieuwegein, Netherlands
Attendance: 38 persons from 8 nations in 3 continents (Australia, Europe and North America)

Opening and Introduction
Mr. Wim van Vierssen, Managing Director of Kiwa Water Research - the hosting partner - welcomed the workshop participants and encouraged them to have stimulating discussions that would lead to results on which to build future research.

Next, Mr. Frans Schulting, Director of the Global Water Research Coalition (GWRC), briefly introduced his organisation and highlighted the importance of the workshop within the framework of GWRC’s research strategy. He described GWRC as a network organisation of research institutes in the field of water supply, sanitation, wastewater treatment and water reuse. The prime objective of GWRC is knowledge management on a global level through exchange of information and knowledge, development of research strategies for global issues, and coordination of research efforts. Currently GWRC has 14 members, viz. three research institutes from the USA, two each from France, Australia and the Netherlands and one each from Germany, Switzerland, the UK, Singapore and the Republic of South Africa. GWRC is an affiliate of the London-based International Water Association (IWA) and has established an official partnership with two important US government institutions, the US Environmental Protection Agency (USEPA) and the Centre for Disease Control and Prevention (CDC). Sensors and on-line monitoring is one of the present main research areas of GWRC. The research on water quality focuses on algal toxins, water-borne pathogens and emerging pollutants (e.g. endocrine disruptors and pharmaceuticals). Other research areas are water quality in distribution systems, waste water treatment (e.g. membrane bioreactors), water reuse, and asset management.

Mr. Theo van den Hoven (Kiwa Water Research, NL) outlined the scope, objectives and setup of the workshop. His starting point was that customers and regulators alike expect water utilities to provide safe drinking water. Meeting these expectations requires robust (multi-barrier) treatment design, proper operation of the treatment and distribution system, and adequate risk management. Water quality and public health risks need to be analysed and minimised, but to do so utilities must have knowledge of their raw water (quality and catchment) and their treatment processes. Ensuring minimal risks in the distribution and domestic plumbing systems is the final step towards safe drinking water.

EWS can be powerful quality control tools, since they provide information before the water is consumed. Water intake protection and treatment process control with sensors and EWS becomes increasingly common, and their potential use as a barrier against terrorist attacks on water systems may be equally important in the future. At present, water quality control is still dominated by laboratory analysis of grab samples. Sensors are only available for a very
limited number of parameters and frequently do not entirely meet the needs of the users. On the other hand there are rapid advances in sensor, integrated components and microelectronics technology, which promise to make comprehensive on-line water quality control an increasingly realistic alternative.

The three partners in the project sensors and on-line monitoring project (Awwa Research Foundation, UKWIR, and Kiwa Water Research) had already performed a couple of surveys, the results of which (in particular reviews of sensor technology, and of utility experiences and needs) were to be presented during the workshop. The programme also included four presentations about monitoring practice examples. It was expected that the input and the feedback from the discussions during the workshop would allow the drawing of a ‘roadmap’ for on-line monitoring research and technology development.

**Examples of Monitoring Practices**

*Water Intake Protection*

Mrs. Corina de Hoogh (Kiwa Water Research, NL) presented an overview of on-line monitoring practices for source water protection in the Netherlands. The rivers Rhine and Meuse, two of the most important sources of drinking water in that country, have large catchments in adjoining countries, so the water quality of these rivers is continuously monitored at their point of entry. In addition, five EWS are operated by the water utilities at all sites where Rhine or Meuse water is abstracted for drinking water production. Intake protection in the Netherlands combines physical sensors (e.g. pH, turbidity, temperature, conductivity) and advanced chemical screening (e.g. LC-MS-MS and SPE GC-MS) with continuous biomonitoring. The biomonitoring systems used cover different trophic levels (bacteria, algae, crustaceans, molluscs, and fish) and their performance (QA/QC) has been improved significantly by means of an elaborate testing and standardisation process. As a result, it has become easier to relate the results of chemical monitoring (for single compounds) with those for biological effects. This was illustrated by two cases of Meuse water contamination, which were initially detected by a biomonitor but could afterwards be assigned to four specific organic compounds, thanks to data from advanced chemical screening (HPLC-DAD combined with QTOF-MS-MS identification) and laboratory research (toxicity tests) Finally Mrs. De Hoogh stressed the importance of AQUALARM, a web-based information system of the Dutch Ministry of Transport and Public Works, which provides water utilities with access to real-time data from the monitoring stations.

*On-Line Monitoring - Distribution*

Mr. John Proctor (Yorkshire Water, UK) described the efforts of his company to monitor water quality changes in its distribution system on-line. Monitoring units have been installed at the inlets of all major distribution areas. Instrumentation includes flow (water balance), pressure (hydraulic calibration), pH, conductivity, redox potential (indicators of chemical change), turbidity, temperature and dissolved oxygen (secondary calibration). Optional parameters are chlorine and UV extinction (254 nm). Wherever possible, the instrument casings are placed in manholes and connected to the water mains via a cable, a plunger handle and a housing assembly with valve. If data transmission is problematic (signal attenuation by manhole cover), a security cabinet for the instrument casing must be placed above ground and connected by cable to the housing assembly in the manhole. Experience has shown that the following aspects are critical: accessibility (easy for utility staff but difficult for unauthorised persons), power supply and communications, control
opportunities, and absence of waste streams. Small-sized and ordinary looking equipment holds great advantages. Yorkshire Water is very satisfied with the results from its on-line distribution monitoring system. It has greatly increased its knowledge of complex processes (e.g. the impact of valve operations on turbidity) to the benefit of day-to-day operations.

Customer Information
Mr. Bruce Johnson (Tucson Water, USA) first sketched the historical background (massive loss of consumer confidence after serious taste and odour problems) of the decision to establish EMPACT, an environmental monitoring system for public access and community tracking, designed to provide the community (720,000 inhabitants) with timely water quality information. A total of 22 automated on-line water quality stations covers the entire distribution network and generates real-time data for chlorine, pH, conductivity and temperature, whereas snapshot laboratory measurements from over 400 sampling stations provide information on additional parameters (e.g., coliforms, fluoride, hardness, nitrate, sodium and total trihalomethanes). The community can easily access these water quality data via the website of the City of Tucson. A simple mouse click on a city map even provides each citizen with individualised information from the sampling point nearest to his residence.

The main benefits of EMPACT are that this multiple use system is able to
- detect water quality changes in real time,
- review multiple data sets simultaneously,
- provide a real time view of the potable water system,
- detect trends,
- allow quick data retrieval for timely decision making,
- integrate new parameters as technology improves.

Security
Mr. John Hall (Environment Protection Agency, USA) reported on the progress of an National Homeland Security Research Centre, Water Infrastructure Protection Division (NHSRC/WIPD) project, which is carried out at a test and evaluation facility in Cincinnati. The major project objectives are to evaluate the capability of commercially available sensors to detect water quality changes resulting from contamination, and to demonstrate dual benefits of improved water quality and security via sensors. Altogether more than 20 commercial systems (involving about 15 different parameters) were tested in a distribution system simulator (DSS) to detect 25 different contaminants (e.g. insecticides, herbicides, bacteria, toxic inorganics) injected into the DSS. It was concluded that it is feasible to build a contaminant warning system (CWS) in the lab which deserves to be tested under field conditions. It was further found that many standard water quality parameters change in response to contaminant injections, but free/total chlorine and TOC were the best overall trigger parameters. It appears that the dual benefits are indeed achievable. In another test series eight commercially available biomonitors were tested for their suitability in the framework of the Water Sentinel Initiative. There are still a number of unsolved issues and challenges. No radioactive substances have been tested for and low concentrations of harmful bacteria and chemicals remain difficult to detect. It is also unclear how the systems perform under (highly variable) field conditions. Finally costs (about $50,000 per monitoring station) must be taken into account. More research is needed, in particular to address gaps in sensor response (radionuclides and biological contaminants) and to evaluate sensor
performance in the field (Water Sentinel pilot). It seems clear that it is essential to combine biosentinel detection with on-line monitoring equipment for standard parameters.

Experiences and Needs of Water Utilities

Experiences
Several months before the workshop a survey was conducted among water utilities in the United States of America, the United Kingdom, the Netherlands and Belgium. These utilities were asked to report whether and how they monitored a list of parameters in various types of water, and how reliable and satisfactory their on-line equipment was (if applicable). The parameter list included about 75 parameters from 7 main groups (e.g. general & inorganic parameters, major ions, individual organic compounds or biological parameters). The six water types were stored raw water (RW), ground water (GW), surface water intake (SW), water treatment - in process (TP), water treatment - final water (FW), and water in distribution system (DS).

In total, 68 utilities participated in the survey (USA 51, UK 7, NL 8, B 2), and the response rate ranged from 20% (USA) to 80% (NL). Detailed presentations of the survey results were given by David Holt (UKWIR, UK results) and Jurgen Volz (Kiwa Water Research, results from USA, NL and B) on the first day of the workshop. The main conclusions were as follows:

- All utilities had some degree of on-line monitoring experience; each and every utility monitored at least one parameter (water flow rate) at one or more stages of its treatment and distribution process. The total number of parameters monitored on-line by a single utility varied between 1 and 16.
- Next to flow rate the vast majority of utilities in all countries also monitored water temperature, conductivity, turbidity and pH on line.
- In general, larger utilities in all countries seemed to monitor a larger number of parameters on line than smaller utilities. The source water type was equally important. Utilities that do not depend on surface water usually monitor fewer parameters on line than comparable utilities with surface water sources. The relative stability of groundwater quality compared to the frequent and sudden changes of surface water quality obviously warrants the adoption of a different monitoring strategy (laboratory measurements for ground waters preferred over on-line measurements).
- The number of parameters monitored on line per country varied greatly. UK utilities reported a total of 22 different parameters, and US utilities a total of 20, whereas the Dutch companies reported only a total of 11 parameters. The on-line monitoring practice in The Netherlands appeared relatively uniform comparable utilities monitored more or less the same six to eight parameters).
- The survey results also revealed other national differences, which were mainly due to different water treatment practices. E.g. the majority of utilities in the UK and USA monitor on line for chemicals such as fluoride, chlorine (or chloramines) and aluminium, which they commonly dose in the course of their treatment process. None of these parameters are monitored on line in the Netherlands, since all water utilities there employ alternative disinfection methods (slow sand filtration, ozone and UV irradiation), and fluoridation of drinking water is legally prohibited. On the other hand, biomonitors and Ca/Mg/Hardness were frequently monitored on line in the
Netherlands, but not in other countries. All surface water utilities in the Netherlands have deployed biomonitors, and water softening is common for excessively hard source waters in the Netherlands.

- In all countries, the majority of utilities ranked the overall performance (in particular reliability) of on-line monitoring equipment for the Top five or Top eight most frequently investigated parameters as ‘good’. The more sophisticated on-line equipment for more ‘exotic’ parameters (e.g. biomonitors, spectral absorption and particle count) usually achieved lower performance rankings.
Needs
Pre-workshop information on the needs of water utilities was restricted to information from the United Kingdom (cf. presentation by David Holt). In the UK the Top three concerns of utilities were the reliability, accuracy cost, ease of use and maintenance of on-line monitoring systems. With regard to water intake and treatment UK utilities felt a need to develop or have access to new or improved sensors for parameters such as low-level organics, pesticides, hydrocarbons, bacteria and disinfection by-products (bromate and trihalomethanes). With regard to water distribution they felt a need to improve process control and reduce customer complaints for parameters like colour, chlorine, iron and manganese, preferably by means of multi-parameter monitoring devices.

Priority Issues
The last two hours of Workshop Day 1 were devoted to identifying research needs and/or priorities in on-line water quality monitoring as perceived by the participants. To facilitate this process, the participants were split into four representative groups; each group was consisted of representatives from research institutes, water utilities and equipment vendors. The brainstorm sessions in these groups yielded a tremendous amount of information about the participants experiences, assessments (desire and hope as well as frustration), and expectations with regard to on-line monitoring. A plenary discussion of this largely unstructured information helped the organisers to cluster a large variety of subjects into the 10 key or priority issues specified below. One or more of these issues were assigned to each of the four groups on Workshop Day 2 in order to develop practical project proposals.

Monitoring and Implementation Strategies & Response Actions (clusters 1-3)
When companies develop monitoring strategies, a consensus existed about the need to clearly distinguish between different drivers, such as regulatory concerns, security issues and operations improvement, and that this must pre-empt cost considerations. It was also considered helpful to compare the current situation with an as yet undefined quality standard (“Good Sensor Practice”, GSP), and to integrate monitoring into vulnerability assessments and water safety plans.

The implementation strategy for sensors was thought to need focusing on operational procedures and knowledge (control of treatment and distribution processes), staff training and learning (evaluation of practical experiences), adequate response actions, and the reduction of false alarms. The response actions themselves ought to be laid down in action plans (including alarm verification procedures) and should be a regular part of staff training and exercise.

Data Transport, Handling, Mining etc. (clusters 4&5)
Telemetric transmission (in encrypted form, if necessary for security reasons) and two-way sensor-control feedback were identified as key factors of data transport. Transforming data into operational information could be improved by processing with neural networks, novel algorithms and hydraulic modelling. In addition, the combination of water quality monitoring data with data from other information systems (e.g. GIS databases, health and drug use statistics, and water utilities’ customer complaints registers) was strongly advocated, although the incompatibility of different systems was clearly identified as a potential matter of concern.
Testing, Validation & Standardization of Sensors (cluster 6)  
The discussions and recommendations regarding this cluster mainly centred on design and evaluation criteria for sensors, differentiation between the requirements of laboratory, pilot-scale and field tests, and on the desirability of truthful information exchange between the developers and users of water quality monitoring systems. Certification and test standardisation were considered to be extremely important in demonstrating to regulatory authorities that on-line equipment can produce high quality data.

Specific Sensors & “The Ultimate Sensor” (clusters 7&8)  
The water utilities’ considered there was an urgent need to develop (or improve) on-line sensors for the following quality parameters: pathogenic organisms, radionuclides, surrogate parameters for toxic or regulated substances, chlorine dioxide, organic substances (nitrogen compounds, hydrocarbons, military agents), metals, taste, odour and colour. With regard to process control and protection of the distribution system against deliberate contamination on-line monitoring of valve (and other vital infrastructure) status was suggested. Sitting of preferably underground or otherwise inaccessible, and power support to (preferably low and independent of public grid), these sensors are of adamant importance.

Regarding the ultimate sensor, it emerged that generic sensors (detecting entire classes of compounds or physiological effects) seem to have definite advantages over specific sensors targeting single contaminants. Small size and independent power supply as well as no maintenance and self-calibration were unanimously agreed features of the ultimate sensor – the “talking tap” which would supply all of the information for the water utilities to provide wholesome and healthy drinking water to each of its customers 24 hours per day, 365 days per year.

Overview & Exchange of information and Know-How (clusters 9&10)  
During the closing ceremony of the workshop the Director of the GWRC, Mr. Frans Schulting, explicitly announced his organization’s willingness to provide an overview of successful on-line monitoring approaches (multiple sensors, compound “libraries”), and to organize a structured, regular exchange of information and know-how, which may eventually culminate in global internet forums and conferences.
b. Agenda

Research strategy workshop
State-of-the-Art Real-time on-line monitoring of contaminants in water

Date: March 22-23, 2007
Venue: Kiwa Water Research, Nieuwegein, The Netherlands

Day 1, 22 March 2007

11.00 Welcome with tea & coffee
11.30 Opening (Wim van Vierssen, Kiwa Water Research)
11.35 Introduction GWRC (Frans Schulting, Global Water Research Coalition)
11.45 Scope, objectives and set up of workshop (Theo van den Hoven, Kiwa Water Research)
12.00 Examples of monitoring practices
   • Intake protection (Corina de Hoogh, Kiwa Water Research)
   • Operation distribution networks (John Proctor, Yorkshire Water)
   • Customer information (Bruce Johnson, Tucson)
   • Security (John Hall, Environmental Protection Agency)
13.15 Lunch
14.15 Questionnaire utility experiences and needs
   • United Kingdom (David Holt, UKWIR)
   • United States of America, The Netherlands and Belgium (Jurgen Volz, Kiwa Water Research)
14.45 Technology review (Bram van der Gaag, Kiwa Water Research)
15.15 Break
15.45 Brainstorm research needs
18.00 Drinks and dinner
19.30 Adjourn

Day 2, 23 March 2007

08.30 Tea & Coffee
09.00 Priority setting research needs
10.00 Break
10.15 Elaboration of research priorities in projects
12.45 Summary and follow-up
13.00 Lunch
c. List of participants

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<thead>
<tr>
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<tr>
<td>Adam Lovell</td>
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<td>David Holt</td>
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<td>Erich Shaw</td>
<td>Lheritier</td>
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<td>Frans Schulting</td>
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<td>Geert Besselink</td>
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<td>Geo Bakker</td>
<td>Vitens</td>
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<td>Gert-Jan Euverink</td>
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<td>Hsiao-wen Chen</td>
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<td>Jeff Swertfeger</td>
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<td>Joep Appels</td>
<td>MicroLAN</td>
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<td>Joep van den Broeke</td>
<td>Scan Messtechnik</td>
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<td>John Hall</td>
<td>U.S. Environmental Protection Agency</td>
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<td>Joost Timmerman</td>
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<td>Jurgen Volz</td>
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<td>Karl Heinz Bareiss</td>
<td>Endress + Hauser Conducta GmbH+CoKG</td>
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<td>Marcel Klein Koerkamp</td>
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<td>Michael Haeck</td>
<td>Hach-Lange</td>
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<td>Michel Jousset</td>
<td>Suez-Environement CIRSEE</td>
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<td>Pankaj Parekh</td>
<td>Los Angeles Department of Water and Power</td>
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<td>Patrick Marcus</td>
<td>DVGW - Technologiezentrum Wasser</td>
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<td>Ron Hunsinger</td>
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d. Presentations
GWRC Workshop
"State-of-the-Art real-time on-line monitoring of contaminants in water"
Frans Schulting
Nieuwegein, 22 – 23 March 2007

Global Water Research Coalition

- Network organisation of water research organisations
- Water supply, sanitation, wastewater treatment and water reuse
- Motto: Global cooperation for the generation of water knowledge

Urban Water Cycle

GWRC Objectives

- Exchange of information and knowledge
- Development of research strategies for global issues
- Coordination of research efforts
- Knowledge management on a global level

The GWRC Members

- Awwa RF (US)
- WERF (US)
- WRF (US)
- Anjou Recherche (Veolia) (FR)
- CIRSEE (Suez) (FR)
- TZW (DE)
- EAWAG (CH)
- Kiwa (NL)
- PUB (SG)
- STOWA (NL)
- UK WIR (GB)
- CRC WQT AU
- WSAA (AU)
- WRC (ZA)
- Coordination of research programs at a (inter) national level

GWRC partners:
US Environmental Protection Agency (July 2003)
Centers for Disease Control and Prevention (July 2005)
Way of Working

• Network Organisation
• Small staff, but large resources
• Contributions by the members
  – Funds and resources
  – Research management – lead agent
  – Support: website, brochure, hosting meetings, etc.
• IWA affiliate (support services and expert groups)
• Governance by Board of Directors

Board at work!

• Annual Business Plan
• Research Agenda
  – Regular update
• Members and partners
• Procedures
  – Research management
  – Monitoring Members Input
  – Board workshops

Research Areas

• Water Quality
  – Algal toxins
  – Origin and fate of water-borne pathogens
  – Emerging parameters (EDC, PHAC, NDMA, …)
• Water Quality in Distribution Systems
• Asset Management
• Sensors – Online Monitoring
• Wastewater Treatment (o.a. MBR)
• Water Reuse
• Water Concepts of the Future => new topics

Research Approach

• GWRC research agenda based on members needs
• Research strategy for priority areas
  – Review of existing knowledge and activities
  – Workshop about knowledge gaps and research needs
  – Portfolio of research projects
• Tailor made project teams with one member as lead agent
• Sharing the results within the GWRC
• Knowledge transfer to stakeholders by the members

“State-of-the-Art real-time on-line monitoring of contaminants in water”

• Research strategy workshop
  – Shop: exchange of information, knowledge and know-how
  – Work: develop a research strategy and set of projects
• Interested members and partners
• Utilities: end-users
• Sensor developers and manufactures!

Global Water Research Coalition

Sharing the power of knowledge!
Global Water Research Coalition

Platform for Coordination of Research and Exchange of Information

The Benefits
- Leverage of expertise and funding
- Prevention of duplication and replication of research
- Address issues which you can not do on your own
- Different view angles and approaches!

GWRC Reports
- Endocrine Disruptors (9)
- Pharmaceuticals (2)
- Algal Toxins (2)
- NDMA (1)
- Waterborne Pathogens (2)
- Asset Management (2)
- Membrane Bioreactors (2)
- Water Reuse (2)

Ongoing Projects
- Endocrine Disruptors – Toolbox Bio-assays
- Pharmaceuticals and PGP – Priority List
- Nitrosamines (Occurrence and Fate)
- Guidance Manual for Management of Toxic Algae
- Algal Toxins – BMAA
- Hardness and CVD
- Sensors and On-line Monitoring
  - Start in 2007:
    - Asset Management (4)
    - Waterborne Pathogens (3)
    - Water Reuse (2)
    - MBR (1)
Scope, objectives and set up of the workshop

GWRC workshop
Nieuwegein
March 22nd, 2007

Theo van den Hoven

Safe drinking water
Meeting regulator and customer expectations

Starts with robust design (multibarriers) and proper operations!

Safety by risk management

Analysing and minimising risks for water quality and public health

Know your catchment
Know your raw water
Know your treatment
Safeguard the distribution system
Safeguard the household plumbing
Safe drinking water

Safety by risk management

On-line water quality monitoring can assist .... Quality control before water is consumed

Sensors and Early Warning Systemen

Intake protection
Process Control
Terror

Booming developments, lots of promises but what is reality?

Current situation:
- periodical samples + laboratory analyses
- use of sensors for limited number of parameters
- requirements of users often not met with available systems

Advances in technology (ICT, microelectronics, a.o.)
new and significantly enhanced sensor capabilities
on-line monitoring water quality real possibility

Many initiatives to explore opportunities

Joining forces
Global Water Research Coalition

Real-time on-line monitoring of contaminants in water

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BTO 2008.028

May 16, 2008
The project
Understand and utilise opportunities

- Partners: UKWIR, AwwaRF, Kiwa WR
- Review what analysis is needed
  - Workshop UK, US
  - Inventory NL
  - GWRC questionnaire
- Determine
  - what is available
  - what needs development
- Present results and develop roadmap in international seminar
  - 22, 23 March 2007

Today and tomorrow

- Examples of monitoring practices
  - Intake protection
  - Operations
  - Customer information
  - Security
- Review utility experiences and needs (questionnaire)
- Technology review

Roadmap research and technology development
Introduction

- Continuous surveillance of surface waters
- Monitors in use
- Recent developments in continuous biomonitoring
- Information exchange
- Results of combined monitoring efforts

On-line monitoring for source water protection in the Netherlands

- Monitoring surface water quality:
  - Rhine
  - Meuse
- Early warning at abstraction points for drinking water

Chemical & physical monitoring

- Chemical screening technologies:
  - LC-MS-MS
  - SPE GC-MS
- Physical sensors:
  - pH
  - Temperature
  - Oxygen
  - Turbidity
  - Electric conductivity

Continuous biomonitoring in use

- Algae
- Mussels
- Bacteria
- Fish

Elaborate testing and standardisation procedures...

- Spike tests show significant deviation of normal behaviour
- Standardisation of organism age in tests

Real-time on-line monitoring of contaminants in water
... have led to major improvements of QA/QC in continuous biomonitoring

Substance monitoring and effect monitoring more closely related

Information exchange between monitoring locations www.aqualarm.nl

Real-time data frequently used by water companies

Result of combined monitoring efforts: identification of unknown toxic component

- Two events in river Meuse:
  - First: Thursday, March 18th – Monday, March 22nd
  - Second: Thursday, April 15th – Thursday April 22nd
- 40-50% of Daphnia died in measuring chamber
- Sensors for pH, Temperature, Oxygen, Electric Conductivity, Turbidity: no abnormalities
- LC-DAD QTOF MS MS: 4 signals different from normal Meuse-samples
  - Hexamethoxymethylmelamine (industrial chemical) - March
  - PMMM: Derivative of HMMM – March
  - Isoproturon - April
  - Unknown substance, retention time 22.4 minutes – March and April

Structure of unknown substance

- 3-cyclohexyl-1,1-dimethylurea
  - Structure confirmed with pure substance
  - Concentration found: 1-5 µg/l
  - March: combination with HMMM / PMMM
  - April: combination with isoproturon
Additional acute static toxicity test using *Daphnia magna*

Article published

On-line continuous (bio)monitoring: tool for source water protection

GWRC-Workshop "State-of-the-Art Real-time on-line monitoring of contaminants in water, Nieuwegein, March 22nd, 2007"
On-line monitoring - Distribution

John Proctor
Yorkshire Water

First Instrumentation

- Flow
- Pressure
- pH
- Conductivity
- Redox potential
- Turbidity
- Temperature
- Dissolved oxygen

- Water balance
- Hydraulic calibration
- Indicators of chemical change
- Readily available
- Secondary calibration

Real-time on-line monitoring of contaminants in water
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May 16, 2008
This is very heavy – a two-man operation – also attenuates signals.
For Non-WTW applications

ACCESS !!!!!

No waste streams

Power

Comms

Control???

Size is important

Small = easier to get into the main

Need to look very ordinary

Closure of 36” outlet main valve
Valving Operations at Daisy Hill - Detail of Initial turns

Initial Closure Turbidity Effects

Closure of 36” outlet main valve

Controlling Turbidity Level

Thank you
Environmental Monitoring for Public Access and Community Tracking

Providing Timely Water Quality Information to the Community

Bruce Johnson

Tucson Water is a department of the City of Tucson which operates as a public utility serving approximately 720,000 people.

- Increased water quality monitoring with a continuous online monitoring system
- Improved time relevancy of public access to water quality data
- Improve community tracking of water quality measurements through tailored reporting of individualized water quality data
- Primary interest to improve water quality awareness in the community

United States EPA Sponsors EMPACT

“Providing the Public with Timely Water Quality Information”

Community Partnerships

What’s the Quality of Our Drinking Water?

And Why is it Important to You?
What is Tucson’s Water Quality?

22 On-line Water Quality Monitoring Stations

What is My Water Quality?

Delivering up to date water quality information on the web from over 400 sampling locations

Water Quality Parameters

- Real Time Online Measurements
  - Chlorine
  - pH
  - Electroconductibility - Total Dissolved Solids
  - Temperature
- Snap Shot Laboratory Measurements
  - Coliform
  - Hardness
  - Nitrate
  - Sodium
  - Total Trihalomethanes - THMs
  - Fluoride

HACH Monitoring System

Real-time on-line monitoring of contaminants in water

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Benefits

- Able to detect water quality changes in real time
- Able to review multiple data sets at one time
- A real time view of the potable system
- Readily see a trend
- Able to integrate data from physical locations using a web based GIS application
- Quick data retrieval to make timely decisions
- Able to add new parameters as technology improves
- Multiple uses

Building our Security Future

- Testing & Evaluating New Technologies
- Building on the EMPACT framework
  - Controlled environment
    - Challenge testing to determine analytical capabilities
  - Distribution System Challenges
    - Operational
    - Technological
    - Environmental
**Project Overview**

- Manage NHSRC research at the Test & Evaluation (T&E) facility (Contract EP-C-04-034 with Shaw Environmental, Work Assignment 06)

- Disseminate knowledge to stakeholder groups through papers, articles, fact sheets, presentations, tours, (AWWA, utilities, national labs, etc)

---

**Research Objectives:**

**Why we did the project**

- Evaluate the ability of commercially available water quality sensors to detect changes in water quality resulting from contamination
- Support decontamination and pathogen persistence on pipe material experiments
- Support OW WaterSentinel Initiative pilot
- Demonstrate Dual Benefits of improved Water Quality and security via sensors

---

**Research Questions**

- Evaluate the feasibility of using commercially available water quality sensors to trigger alarms (Contaminant Warning System) due to changes in water quality parameters resulting from contamination events
- What happens when various contaminants are introduced into the water supply
- What standard water quality parameters are the most effective for detecting changes in water quality

---

**What is the T&E Facility?**

- Dedicated in 1979 at the Sewer Plant for pilot scale testing (24,000 sq. ft high bay)
- Shaw Environmental Inc. operates facility
- Facility includes 6 recirculating loops, 2 single pass lines, 1 decontamination loop, 2 environmental chambers, 4 on site labs (GC,IC w/MS, BSL-2), greenhouse, mobile fermenter, Biosentinel (fish, clams, daphnia, algae) package plant treatment systems (UV, ozone, filtration), and Ohio RCRA Treatability Exclusion

---

**Distribution System Simulator**

Real-time on-line monitoring of contaminants in water

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Single Pass Pipe

• 1200 feet of 3 inch cast iron pipe
  • Flow is 1 ft/sec
• Sensors are located at 80 and 1100 ft from the injection point
  • Sensors only see the contaminants once
  • Spatial differences can be observed
• Contaminants injected with a pump

Sensors Tested

• Instrumentation:
  • ATI A-15 Free chlorine analyzer
  • Hach CL-17 Free chlorine analyzer
  • Hach Astro TOC analyzer
  • Hach Aquatrend Panel (multi parameter)
  • Dascore Six Cense sonde (multi parameter)
  • Insitu Troll 9000 Sonde (multi parameter)
  • Hydrolab Datasonde 4a (multi parameter)
  • YSI 6600 and 6920 (multi parameter)

Sensors Tested (Continued)

• S::CAN Spectro:Lyser and Carbo:Lyser
• JMAR BioSentry
• Fluid Imaging Flow Cam Device
• GE/ Sievers 900 and 500 TOC
• ZAPS
• Hach Laser Turbidimeter
• Hach Particle counter

ETV Testing at T&E

• Rosemount multi probe
• Clarion/Prominent multi probe
• Mantech multi parameter equipment
• Hach Aquatrend Panel and Event Monitor System
• ATI multiprobe

On-line Standard Water Quality Test Parameters

• pH, temperature, pressure
• ORP, specific conductance
• Turbidity, particle counts,
• free & total chlorine
• TOC
• ammonia (NH4+-N)
• nitrate (NO3--N)
• chloride (Cl-)
• UV/vis absorption/ fluorescence

Action Photos

Real-time on-line monitoring of contaminants in water

Glyphosate in chlorinated water

January 22, 2004 Glyphosate Injection*
Free Chlorine and Associated Grab Sample Results

Malathion vs. TOC

January 9, 2004 Malathion Injection*
Total Organic Carbon and Associated Grab Sample Results

Bio Sentry Trial Runs

Project Approach

• Various contaminants are injected into distribution system simulators and the response of online WQ sensors are observed and recorded.
• To date over 20 sensors (14 vendors) using multiple principles of detection have been tested versus 25 contaminants. (17 WQ parameters)

Publications and Products

• 2 Articles on Pipe Material Decontamination (Environmental Science and Technology, Applied and Environmental Microbiology)
• 1 Journal of the AWWA sensor Article (January 2007)
• Reports on the WaterISAC
  • Sensor response in recirculating DSS loop (2)
  • Minimum Dose
  • Single Pass
  • Edgewood Water Test Loop Report Summary
• Comparison of chlorinated and chloraminated water quality responses to contaminants (AWWA Water Congress)
Injected Contaminants (0.2 to 4 mg/l)
- Bacteria
  E.coli
  B.globigii
- Insecticides
  Aldicarb
  Dichlorvos
  Phorate
  Malathion (neat)
  Real Kill®
- Herbicides
  Glyphosate (neat)
  Round-Up®
  Dicamba
- Culture Broths
  Nutrient
  Terrific
  Trypticase Soy
  Spore Media
  YPXD
- Inorganics
  Lead Nitrate
  Mercuric Chloride
  Arsenic Trioxide
  Ferricyanide
- Herbicides
  Cyanide (KCN)
  VX
  GB (Sarin)

Injected Contaminants (cont’d)
- Others
  DMSO
  Sucrose
  Nicotine
  Colchicine
  Humic Acid
  Ascorbic Acid
  Sodium Thiosulfate
- ECBC Contaminants
  VX
  GB (Sarin)
  KCN
  Ricin (0.25 mg/l)

Sensor Response in the Recirculating Loop

Research Conclusions
- It is feasible to build a Contaminant Warning System (CWS) in the lab and warrants field testing (Water Security Initiative “Sentinel”)
- Many Standard WQ Parameters change in response to contaminant injections
- Free/ total Chlorine and TOC were the best overall trigger parameters
- “Monitoring is Good” Dual Benefits are achievable

Issues and Challenges
- No Radiological testing done
- Washed Biological Contaminants (less than 10⁵ CFU/ml)
- Harmful contaminants at less than 1 mg/L
- Field Variability and unstable parameters
- Severe run to failure testing for field conditions (monthly maintenance)
- Only 1 Event Detection Algorithm tested by EPA to date
- Monitoring stations are ~$50K each

Water Sentinel Initiative Configuration (8 so far)

Future Plans

• Address gaps in sensor response (Rad and Bio)
• More study on pathogen adhesion and decontamination
• Evaluate sensor performance in the field during WaterSentinel pilot
• Additional Algorithm Testing
• Biosentinel detection and Standard WQ equipment
‘State of the Art’ Real-time on-line monitoring of contaminants in water

UK Water Company Experiences and Needs

Dr David Holt
UKWIR Project Manager

Content of Talk

- Background of UKWIR research
- Findings from earlier project
- UKWIR Water Company questionnaire
- Instrument supplier company questionnaire

Project Background

- UKWIR Projects
  - 05/06 – “Rapid Analytical Response in Emergency Situations”
  - 06/07 – Collaborative review ‘State of the Art’ Real-time on-line monitoring of contaminants in water
  - 07/08 – “Risk Studies and intake protection”

Rapid Analysis

Rapid Analysis - Objectives

- Review existing literature and ongoing studies on analytical techniques.
- Evaluate available technology for rapid screening based on rapidity, robustness, LOD, accuracy and propensity to produce false positive/negative results.
- Provide the industry with advice on rapid robust screening techniques, practical guidance and awareness.

Rapid Analysis – Findings (1)

- Providing a rapid result for the absence of chemical, radiological and microbiological contamination is difficult
- Screening tests should be robust with minimal false positives or negatives
- To convincingly prove a negative in a short time, rapid screening tests are considered essential
- There is no universal toxicity monitor
Rapid Analysis – Findings (2)

- Although on site test kits have their value the overall coverage is limited compared to the laboratory
- On-site screening is only suitable for targeted analysis (i.e. when the parameter being analysed for is known).
- Mobile laboratories with a whole suite of test kits and simple screening techniques are not considered to be either viable or cost-effective for low frequency emergency incident events.
- Preference is to take the sample to the laboratory where more extensive analytical equipment is available.

Water Company Questionnaire

- Questionnaire developed with Kiwa.
- Look at UK needs for on-line monitoring and laboratory analysis requirements.
- Requirements determined for:
  - Stored water
  - Groundwater
  - Surface Water
  - Through treatment
  - Final (finished treated water)
  - Distribution

Questionnaire Aims

- Aims
  - To identify UK instrument needs for on-line monitoring of water quality parameters.
  - Part of an exercise in gathering information from users in the UK, USA and Netherlands.
  - To provide a basis for the UKWIR project “Risk Studies and intake protection”.
- Survey
  - Involved 8 water companies.
  - Large and small companies responded.
  - Questionnaire followed by Workshop.
  - Collected data for on-line and laboratory monitoring.

On-line Instrumentation (1)

<table>
<thead>
<tr>
<th>Parameter measured</th>
<th>Stored Water</th>
<th>Ground water</th>
<th>Surface Water</th>
<th>Treatment</th>
<th>Final Water</th>
<th>Distribution</th>
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<td></td>
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<td></td>
<td></td>
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On-line Instrumentation (2)

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</tbody>
</table>

Instrument Supplier Survey *

- Aims
  - Determine Customers expectations.
  - How customers needs for new sensors are changing.
  - Drivers for monitoring (Regulatory and corporate and operational trends).
- Survey
  - Involved 7 water companies, the regulator and 3 major contractors.
  - Face to face and telephone interviews.
  - Data analysis based on 37 interviews.

* Acknowledgement to Guy Forrest – Hay ST Services.
Ranking of attributes

- Low level organics
- Pesticides
- Hydrocarbons
- Bromates
- Ozone
- Total nitrogen
- Uv 254
  - AC
  - Nitrate
- DOC
- THMs
- On-line bacteria measurement

Intake and treatment

- Drivers to improve control and reduce customer complaints for:
  - Colour
  - Chlorine
  - Iron
  - Manganese
- Multi-parameter devices

Distribution system

- Reliability of instruments was a major characteristic identified by many water companies
- Both surveys identified that those parameters currently monitored were still key requirements
- Intake protection and monitoring through treatment continue to be the focus for on-line monitoring
- Drinking Water Safety Plans seen as a driver for more monitoring of raw waters and treatment processes

Conclusions
Utility Survey Results
USA, Netherlands, Belgium
GWRC Workshop, Nieuwegein, Netherlands
22-23 March 2007

Survey Method
- Questionnaire on on-line water quality monitoring sent to 250 utilities in USA & 14 utilities in NL+B
- Which parameters are monitored on-line? Where?
  Performance rating?
- Response rate: USA >20%, B 50%, NL 80%
- Survey results are suitable input for GWRC project

Questionnaire Design
- 6 Water ‘types’
  - Stored raw water (RW)
  - Ground water (GW)
  - Surface water (SW)
  - Treatment, in process (TP)
  - Treatment, final water (FW)
  - Distribution system (DS)
- 73 Parameters
  - Opportunity to add parameters

Percentage utilities per size class
USA
(N = 51)

I. ‘Mega’ utilities (> 1,000,000 MGD)
II. ‘Large’ utilities (100,000-300,000 MGD)
III. ‘Average’ utilities (50,000-100,000 MGD)
IV. ‘Small’ utilities (< 50,000 MGD)

Percentage utilities per source water type
USA
(N = 52)

NL + B
(N = 10)

I. ‘Mega’ utilities (> 1,000,000 MGD)
II. ‘Large’ utilities (100,000-300,000 MGD)
III. ‘Average’ utilities (50,000-100,000 MGD)
IV. ‘Small’ utilities (< 50,000 MGD)
Water production per size class

USA
(N=51)

NL + B
(N=10)

Total production
6,450 MGD
855 MGD

Top 10 parameters monitored on-line

Parameter
Flow rate
Turbidity
pH
Water temperature
Conductivity
Fluoride
Oxygen
Chlorine
TOC

Rank (%)
1 (100)
2 (89)
3 (85)
4 (77)
5 (37)
7 (21)
8 (17)
9 (14)
10 (14)

Parameter
Flow rate
Turbidity
pH
Water temperature
Conductivity
Fluoride
Oxygen
Chlorine
TOC

Rank (%)
1 (100)
2 (100)
3 (90)
5 (86)
6 (60)
7 (50)
8 (50)
9 (30)
10 (30)

Other parameters monitored on-line

Parameter
Algae/chlorophyll
Ammonium
Nitrate
Chloride
Volatile halogenated hydrocarbons
VOCs (FID detector)
Chloramine
"Streaming current detector"
DOC
Redox potential

No. of Utilities
4
3
2
1
1
1
1
1
1
1

Deployment of on-line monitors

Utilities
USA
NL + B

Deployment rate %
52
46
41
40
20
9
19
6
11
7
0
0

Parameter
Flow rate
Turbidity
pH
Water temperature
Conductivity
Fluoride
Oxygen
Chlorine
TOC

Deployment rate %
76
59
55
57
27
39
12
10
18
n.a.
n.a.

Size class differences

Class
USA
NL + B
USA
NL + B

Average no. of parameters
(3-8)
62
(28-100)
53
(36-63)

Average deployment %
(55-60)
56
(3-10)
41
(8-11)
44
### Source water differences

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<thead>
<tr>
<th></th>
<th>N</th>
<th>Average MGD (range)</th>
<th>Average no. of parameters (range)</th>
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<td>6</td>
<td>50 (12-134)</td>
<td>3.0 (1-7)</td>
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<td>115 (43-296)</td>
<td>7.4 (6-8)</td>
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### Performance of on-line monitors

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<th>Parameter</th>
<th>Percentage 'GOOD'</th>
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Technology review

Nieuwegein
March 22nd, 2007

Bram van der Gaag

GWRC workshop on-line monitoring

The ultimate sensor

Drivers!

Distribution

Security

Review summary

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<tr>
<th>Multi parameter</th>
<th>Innovations</th>
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<td>+/-</td>
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<td>Raman spectroscopy</td>
<td>+/-</td>
<td>R &gt;&gt; B</td>
<td>+/-</td>
<td>+/-</td>
</tr>
<tr>
<td>Multi Angle Light Scattering</td>
<td>+/-</td>
<td>R &gt;&gt; B</td>
<td>+/-</td>
<td>+/-</td>
</tr>
</tbody>
</table>

The practice

Operation & Maintenance

Data
- Handling
- Mining

Measurement types
- Concentration
- Differentiation
Operation & Maintenance

- Questionnaires, workshops
- High operational & maintenance
  - Labour
  - Part replacement
  - Calibration
- Main concern
  - TOC
  - Oxygen
  - Particle count
  - pH
  - Chlorine

Data

Which, how much?

- Monitoring unit
- Source
- Treatment
- Support System
- Data Handling & Interpretation Unit
- Tap water
- Distribution unit
- Monitoring unit

Langelier Saturation Index

Formula

- $LSI = pH - pH_s$
- Where: $pH$ is the measured water pH
- $pH_s$ is the pH at saturation
- $pH_s = (9.3 + A + B) - (C + D)$
- Where: $A = \frac{\text{Log10}[TDS] - 1}{10}$
- $B = -13.12 \times \text{Log10}(°C + 273) + 34.55$
- $C = \text{Log10}[\text{Ca}^2+ \text{as CaCO}_3] - 0.4$
- $D = \text{Log10}[\text{alkalinity as CaCO}_3]$

Data handling

- Excel based programme
- Control of LSI by comparing results from
  - Laboratory measurement
    - Conductivity
    - Carbonate
    - Calcium
    - pH
    - Temperature
  - On-line measurements
    - Temperature
    - pH

Langelier Saturation Index

Practical use

- Measurement error $= \pm 0.1$
- Permitted exceeding $= \pm 0.2$
- Average over 5 years
  - Minimum
  - Maximum
- Calculation of saturation pH
  - Per 0.1°Celsius
- Deviations $< \pm 0.1$
- Only pH measurement and table with temperature related $pH$

Langelier Saturation Index

Data reduction

- Excel based programme
- Control of LSI by comparing results from
  - Laboratory measurement
  - Conductivity
  - Carbonate
  - Calcium
  - pH
  - Temperature
  - On-line measurements
    - Temperature
    - pH
Langelier Saturation Index
Data control

Measurement types
Concentration measurements

Measurement types
Differentiation measurements

Performance indicators

Real-time on-line monitoring of contaminants in water
© Kiwa Water Research - 173 -
BTO 2008.028
May 16, 2008
Warming up for the brainstorm

Thinking ahead
New ideas (1), Transponders, sensors, GPS

Thinking ahead
New ideas (2), µChemLab Separation Instrument

Thinking ahead
New ideas (2), Nanotechnology
GWRC workshop on-line monitoring Processes

Problem to be solved

Measurement → Actuator

Data

Visa or …..

Measurement

Actuator

Data

Guidance (1)

- Define Risk (and trigger values) or Process Control Element
- Is On-line monitoring the best way to monitor
- Select parameter(s) to monitor
- Define measurement specification
- Are instruments available to meet the specifications?

Guidance (2)

- Address implementation issues
  - Location(s)
  - Physical requirements
  - Sampling system
  - Data – communication, storage
  - Maintenance
  - What do you do when the alarm goes off?
  - Exercises
- Cost/benefit analysis
- Proceed with selected alternative

Gaps definition (1)

- Viability and identification of micro-organisms
  - Is there a way to combine viability tests and micro-organism identification?
- Development of new monitoring strategies
  - New technologies change our view on monitoring strategies
  - More information on a specific contaminant may well emerge from on-line monitors.
  - Legislation demands laboratory confirmation
  - Laboratory analysis can be simplified based on on-line monitoring results
Gaps definition (2)

- Plug and Play
  - Instrumentation
  - Data communication
  - Data evaluation
    - Measured data
    - GIS
- ?????
- Look beyond the horizon of analytical traditions
GWRC Workshop
“State-of-the-Art real-time on-line monitoring of contaminants in water”

Follow Up
Nieuwegein, 22 – 23 March 2007

Project proposals
- Development and implementation of monitoring strategies (Ron Hunsinger)
- Testing, validation and standardization of sensors (Pankaj Parekh)
- From data to know-how (Peter Boruszenko)
- Sensor development (David Holt)
- Regular exchange of information (Theo van den Hoven)

Project proposals
- Follow up
  - Finals drafts by May 1 (group action)
  - Review by all participants by 1 June (all)
  - Final proposals by 1 July (group action)
  - Send to all workshop participants (Bram)
  - Together with research strategy => GWRC Board (Theo/Frans)
  - Inventory of formal member commitments (August)
  - Contacts with other parties (August/…)

Workshop report
- Workshop report (draft by Bram)
  - Map of knowledge and experiences
  - Gaps and needs => priorities and research strategy (road map)
  - Suite of project proposals
  - Presentations as annex (pdf)
  - Draft available by 1 May
  - Review by participants by 1 June
  - Final report available to members/partners and workshop participants by 1 August

Follow up actions
- Email with agreed actions to workshop participants by 28 March (Bram)
  - Project proposals by 1 May – 1 July
  - Workshop report by 1 August (2007)
  - Next workshop/meeting in 2008
Platform for Coordination of Research and Exchange of Information

Thanks and have a safe trip back home !!!!

Global Water Research Coalition

www.globalwaterresearchcoalition.net
e. Photos
IV. Questionnaire synthesis

a. UK survey

Introduction
A survey was carried out to document the UK water utilities' current on-line water quality monitoring status. A questionnaire (xls.file) was sent to 15 utilities, 7 of which (ca. 47%) returned a completed questionnaire. Those companies returning questionnaires ranged from large water and wastewater treatment companies to smaller water suppliers.

Questionnaire
Respondents were asked to indicate if their utility monitored a list of parameters in water either on-line and/or in the laboratory. Information was requested for six different points through the drinking water process; 'stored raw water' (RW), 'ground water' (GW), 'surface water intake' (SW), 'water treatment - in process' (TP), 'water treatment - final water' (FW), and 'water in distribution system' (DS). If the analysis was by on-line instrumentation, the utility was asked how reliable the on-line equipment was. The parameter list included a range of parameters from 7 main groups (e.g. General & Inorganic Parameters, Major Ions, Nutrients, Taste & Odour). Some utilities added analytes that did not appear on the survey but were monitored for.

Results
Utility type
Seven water utilities provided responses and these are mainly considered a representative sample of the companies in the UK both in respect to their operational size and source water type. One UK water company that did not complete the questionnaire but was represented at the Strategic Workshop carries out significant on-line monitoring in distribution networks for several water quality parameters. The seven utilities included water sources from ground water, surface derived stored water and directly abstracted river water.

On-line Monitoring
The results of the questionnaire are presented in Table 1. Five water quality parameters, water flow, turbidity, pH, pressure and chlorine were monitored on-line by all the utilities in at least one water type. Temperature (6), conductivity (5), iron (5), Oil in water (4) and nitrate (4) were the other major parameters monitored on-line.

Table IV-1 shows the location of on-line monitoring equipment used by the 7 utilities at different stages of the water supply process, water source through to the distribution network. From the table it is clear that different parameters are required to be monitored at different stages of drinking water production. Monitoring of source water is generally for major pollutants or for a surrogate parameter to indicate major pollution. Through the treatment process chemicals removed or added e.g. iron or aluminium are monitored. Finally chlorine residual is measured both going into, and often in, the distribution network.
The UK Water companies were also asked to give an indication of the performance of the on-line equipment based on ease of use, reliability, accuracy of results and maintenance requirements. The findings are presented in Table IV-2. All instruments were reported as performing Good or Good/average with the exception of Oil on water which was described as Poor. It is of interest that equipment was rated in a similar manner on its performance irrespective of where the instrument was located in the water production process.

A more critical view of performance was given by water companies at the UK Workshop. For a number of parameters, spectral analysis, oxygen monitors, chlorophyll a, particle counts, ammonia and oil in water, where equipment is used at fewer locations in the supply process, the instruments were seen as less reliable. Water Companies also expressed the view that new instruments coming to market were not thoroughly tested for the environments in which they were to be exposed. In many cases the Water Company had to undertake its own trials to demonstrate reliability and determine maintenance frequencies of the equipment at one or more test sites.

Table IV-2: Summary of the UK Survey questionnaire performance of on-line measurements at water utilities (expressed as number of utilities (maximum = 7).
<table>
<thead>
<tr>
<th>Parameter monitored on-line</th>
<th>Stored Water</th>
<th>Ground Water</th>
<th>Surface Water</th>
<th>Process Treatment</th>
<th>Final Water</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Rate</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Turbidity</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
</tr>
<tr>
<td>PH</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
</tr>
<tr>
<td>Chlorine</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
<td>Ave/Good</td>
</tr>
<tr>
<td>Pressure</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Water Temperature</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Conductivity</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Iron</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Nitrate</td>
<td>Good/Ave</td>
<td>Good/Ave</td>
<td>Good/Ave</td>
<td>Good/Ave</td>
<td>Good/Ave</td>
<td>Good/Ave</td>
</tr>
<tr>
<td>Oil on water</td>
<td>Poor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ammonium</td>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orthophosphate</td>
<td></td>
<td>Good/Ave</td>
<td>Good/Ave</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manganese</td>
<td>Good</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>Average</td>
<td>Average</td>
<td>Average</td>
<td></td>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>DOC</td>
<td>Good/Ave</td>
<td>Good/Ave</td>
<td>Good/Ave</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectral absorbance</td>
<td>Average</td>
<td>Average</td>
<td>Average</td>
<td></td>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>Aluminium</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Good</td>
</tr>
<tr>
<td>Particle counts</td>
<td></td>
<td>Average</td>
<td>Average</td>
<td></td>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>Flouride</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Good</td>
</tr>
<tr>
<td>Chlorophyll a</td>
<td>Average</td>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
b. US survey

Introduction
A survey was carried out to document US water utilities' current water quality monitoring status and anticipate their needs for state-of-the-art online monitoring technologies. A questionnaire (in the form of a Microsoft® Excel® file) was sent to approximately 250 utilities, 52 of which (ca. 20%) completed and returned the questionnaire.

Questionnaire
The respondents were asked to indicate whether and how their utility monitored a list of parameters in various types of water, as well as how reliable the on-line equipment was (if applicable). The parameter list included about 75 parameters from seven main groups (e.g. general & inorganic parameters, major ions, or nutrients). The six water types were stored raw water (RW), ground water (GW), surface water intake (SW), water treatment - in process (TP), water treatment - final water (FW), and water in distribution system (DS).

Results
Utility type
The 52 utilities represented a wide variety, ranging from relatively small and simple ground water systems to very large utilities dealing with all six water types (Figures IV-1 and IV-2).

![Figure IV-1: Distribution of number of monitored 'water types' in the USA (N=52)](image-url)
On-line Monitoring

The parameter most frequently monitored on-line was the **water flow rate**. All respondents (N=52) reported on-line monitoring of this parameter in at least one water type. The theoretical maximum of monitoring sites (all water types of all utilities added up) is 241. The actual number of monitoring sites reported by the 52 utilities was 180 (74.7% of the theoretical maximum). The reliability of the on-line flow meters was high (78.9% ranked as 'good', 16.7% as 'average' and 4.4% unspecified).

Turbidity ranked second in on-line monitoring frequency. Forty-six utilities reported a total of 140 monitoring sites (58.1% of potential number of sites). The reliability of the on-line turbidity meters was ranked as: 75.7% 'good', 17.9% 'average', and 6.4% unspecified.

On-line monitoring of **pH** ranked third, with 41 utilities reporting a total of 129 monitoring sites (53.5% of potential sites). The reliability of on-line pH meters was ranked as: 65.9% 'good', 26.4% 'average', 3.9% 'poor', and 3.9% unspecified.

**Water temperature** ranked fourth, with 40 utilities reporting a total of 109 monitoring sites (45.2% of potential sites). Equipment reliability was described as: 84.4% 'good', 11.0% 'average', 0.9% 'poor', and 3.7% unspecified.

Next came **conductivity**, with 20 utilities reporting a total of 42 monitoring sites (17.4% of potential sites). Equipment reliability was described as: 64.3% 'good', 23.8% 'average', 2.4% 'poor', and 9.5% unspecified.

The last parameter which was monitored on line relatively often was **particle count**. Nineteen utilities reported a total of 38 monitoring sites (15.8% of potential sites). The reliability of particle counters was comparatively low: 39.5% 'good', 36.8% 'average', 18.4% 'poor', 2.6% 'bad', and 2.6% unspecified.
The data from this section are summarized in Table IV-3. It also includes the data on parameters, which are seldom monitored on line but were reported by at least one utility.

Table IV-3: Summary of American investigation on use and performance of on-line measurements at water utilities.

<table>
<thead>
<tr>
<th>Parameter monitored on-line</th>
<th>Number of utilities (N = 52)</th>
<th>Number of sites (N = 241)</th>
<th>Equipment reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water flow rate</td>
<td>52 (100%)</td>
<td>180 (74.7%)</td>
<td>Good (142 (78.9%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average (106 (57.7%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Poor (25 (12.7%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bad (8 (4.4%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Not specified (6 (4.4%))</td>
</tr>
<tr>
<td>Turbidity</td>
<td>46 (88.5%)</td>
<td>140 (58.1%)</td>
<td>Good (106 (75.7%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average (106 (75.7%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Poor (25 (17.9%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bad (9 (6.4%))</td>
</tr>
<tr>
<td>pH</td>
<td>41 (78.8%)</td>
<td>129 (53.5%)</td>
<td>Good (85 (65.9%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average (34 (26.4%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Poor (5 (3.9%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bad (5 (3.9%))</td>
</tr>
<tr>
<td>Water temperature</td>
<td>40 (76.9%)</td>
<td>109 (45.2%)</td>
<td>Good (92 (84.4%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average (12 (11.0%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Poor (25 (17.9%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bad (4 (3.7%))</td>
</tr>
<tr>
<td>Conductivity</td>
<td>20 (38.5%)</td>
<td>42 (17.4%)</td>
<td>Good (27 (64.3%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average (10 (23.8%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Poor (1 (2.4%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bad (4 (9.5%))</td>
</tr>
<tr>
<td>Particle count</td>
<td>19 (36.5%)</td>
<td>38 (15.6%)</td>
<td>Good (15 (39.5%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average (14 (36.8%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Poor (7 (18.4%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bad (1 (2.6%))</td>
</tr>
<tr>
<td>Fluoride</td>
<td>11 (21.2%)</td>
<td>12 (5.0%)</td>
<td>Good (9 (75.0%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average (1 (8.3%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Poor (1 (8.3%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bad (2 (16.7%))</td>
</tr>
<tr>
<td>Oxygen</td>
<td>9 (17.3%)</td>
<td>17 (7.1%)</td>
<td>Good (9 (52.9%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average (5 (29.4%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Poor (3 (17.6%))</td>
</tr>
<tr>
<td>Chlorine</td>
<td>7 (13.5%)</td>
<td>16 (6.6%)</td>
<td>Good (13 (81.3%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average (1.5 (9.4%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Poor (1.5 (9.4%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bad (5 (35.7%))</td>
</tr>
<tr>
<td>TOC</td>
<td>7 (13.5%)</td>
<td>14 (5.8%)</td>
<td>Good (3 (21.4%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average (6 (42.9%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Poor (5 (35.7%))</td>
</tr>
<tr>
<td>Spectral absorption/UV 254 nm</td>
<td>6 (11.5%)</td>
<td>10 (4.1%)</td>
<td>Good (8 (80.0%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average (1 (10.0%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Poor (1 (10.0%))</td>
</tr>
<tr>
<td>Algae/chlorophyll</td>
<td>3 (5.8%)</td>
<td>7 (2.9%)</td>
<td>Good (6 (85.7%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average (1 (14.3%))</td>
</tr>
<tr>
<td>Ammonium</td>
<td>3 (5.8%)</td>
<td>5 (2.1%)</td>
<td>Good (1 (20.0%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average (4 (80.0%))</td>
</tr>
<tr>
<td>Nitrate</td>
<td>2 (3.8%)</td>
<td>5 (2.1%)</td>
<td>Good (2 (40.0%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average (3 (60.0%))</td>
</tr>
<tr>
<td>Chloride</td>
<td>1 (1.9%)</td>
<td>3 (1.2%)</td>
<td>Good (3 (100%))</td>
</tr>
<tr>
<td>Volatile halogenated hydrocarbons</td>
<td>1 (1.9%)</td>
<td>3 (1.2%)</td>
<td>Average (3 (100%))</td>
</tr>
<tr>
<td>VOCs [FID detector]</td>
<td>1 (1.9%)</td>
<td>3 (1.2%)</td>
<td>Good (3 (100%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average (3 (100%))</td>
</tr>
<tr>
<td>Chloramine</td>
<td>1 (1.9%)</td>
<td>2 (0.8%)</td>
<td>Good (1 (50.0%))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average (1 (50.0%))</td>
</tr>
<tr>
<td>&quot;Streaming current detector&quot;</td>
<td>1 (1.9%)</td>
<td>1 (0.4%)</td>
<td>Average (1 (100%))</td>
</tr>
<tr>
<td>DOC</td>
<td>1 (1.9%)</td>
<td>1 (0.4%)</td>
<td>Average (1 (100%))</td>
</tr>
<tr>
<td>Redox potential</td>
<td>1 (1.9%)</td>
<td>1 (0.4%)</td>
<td>Average (1 (100%))</td>
</tr>
</tbody>
</table>
c. Belgian & Dutch survey

Introduction
A survey was carried out to document Dutch and Belgian water utilities' current water quality monitoring status and anticipate their needs for state-of-the-art online monitoring technologies. A questionnaire (in the form of a Microsoft® Excel® file) was sent to 11 utilities in the Netherlands and 4 utilities in Belgium. Seventy percent of the Dutch utilities and 50% of the Belgian utilities returned a completed questionnaire. The total number of water utilities in the Netherlands is 11. They serve a total population of 16 million people (i.e. 99.9% of all households)

Questionnaire
The respondents were asked to indicate whether and how their utility monitored a list of parameters in various types of water, as well as how reliable the on-line equipment was (if applicable). The parameter list included about 75 parameters from seven main groups (e.g. general & inorganic parameters, major ions, or nutrients). The six water types were stored raw water (RW), ground water (GW), surface water intake (SW), water treatment - in process (TP), water treatment - final water (FW), and water in distribution system (DS).

Results
Utility type
The nine utilities were a representative sample of water utilities in the Netherlands and Belgium, both with respect to their operational size and to their types of source water (Figure IV-3). The annual water production of these utilities is in the range of 50 to 500 million cubic metres. The population they serve ranges from 200 thousand to 5 million people.

On-line Monitoring
The parameter most frequently monitored on-line was the water flow rate. All respondents (N=9) reported on-line monitoring of this parameter in at least one water type. The theoretical maximum of monitoring sites (all water types of all utilities added up) is 45. The
The actual number of monitoring sites reported by the 9 utilities was 33 (73.3% of the theoretical maximum). The reliability of the on-line flow meters was high (69.7% ranked as 'good', 12.1% as 'average' and 18.2% unspecified). All SW intakes (N=6) were monitored on line (reliability 66.7% good, 16.7% average, 16.7% unspecified). The according scores for the other water types were: FW 88.9% (62.5% good, 12.5% average, 25% unspecified), GW 85.7% (100% good), TP 66.7% (66.7% good, 16.7% average, 16.7% unspecified), DS 66.7% (50% good, 16.7% average, 33.3% unspecified), and RW 33.3% (100% good).

Eight out of 9 utilities (88.9%) reported on-line monitoring of **turbidity**. The actual number of monitoring sites reported by them was 23 (51.1% of the theoretical maximum). Equipment reliability was high (82.6% ranked as 'good', 17.4% unspecified). The scores per water type were: SW 83.3% (80% good, 20% unspecified), TP and FW 66.7% (each 80% good, 20% unspecified), GW 42.9% (100% good), RW 33.3% (100% unspecified), and DS 22.2% (100% good).

Seven out of 9 utilities (77.8%) reported on-line monitoring of **water temperature**. The number of monitoring sites was 22 (46.7% of potential sites). Equipment reliability was high (77.3% ranked as 'good', 22.7% unspecified). The scores per water type were: SW 83.3% (80% good, 20% unspecified), RW 66.7% (50% good, 50% unspecified), FW 55.6% (80% good, 20% unspecified), DS 44.4% (75% good, 25% unspecified), GW 42.9% (100% good), and TP 33.3% (66.7% good, 33.3% unspecified).

The parameter **oxygen** was monitored on line by six utilities (66.7%), which reported 14 monitoring sites (31.1% of potential sites). Equipment reliability was high (71.4% ranked as 'good', 14.3% as 'average', and 14.3% unspecified). The scores per water type were: SW 66.7% (75% good, 25% unspecified), TP 55.6% (60% good, 20% average, 20% unspecified), FW 33.3% (100% good), and DS 22.2% (50% good, 50% average).

**Conductivity** was also monitored by six utilities (66.7%) which reported 11 monitoring sites (24.4% of potential sites). Equipment reliability was excellent (90.9% good, 9.1% average). The scores per water type were: TP 44.4% (100% good), FW 33.3% (100% good), DS 22.2% (50% good, 50% average), SW 16.7 % (100% good), and GW 14.3% ((100% good).

Four utilities (44.4%) reported on-line monitoring of **calcium/magnesium or total hardness**. The number of monitoring sites was 7 (15.6% of potential sites). Equipment reliability was unimpressive (14.3% good, 42.9% average, 42.9% unspecified). The scores per water type were: TP 33.3% (33.3% good, 33.3% average, 33.3% unspecified), FW 33.3% (66.7% average, 33.3% unspecified), and DS 11.1% (100% unspecified).

Four utilities (44.4%) also reported the deployment of (1 or 2) on-line **biomonitors**. The number of monitoring sites was 5 (11.1% of potential sites). Equipment reliability was unimpressive (20% good/bad [two systems on one site; one good, one bad], 60% average,
20% unspecified). The scores per water type were: SW 66.7% (25% good/bad, 50% average, 25% unspecified), and RW 33.3% (100% unspecified).

Three utilities (33.3%) reported the deployment of on-line particle counters. The number of monitoring sites was 6 (13.3% of potential sites). Equipment reliability was high (83.3% good, 16.7% average). The scores per water type were: TP 33.3% (66.7% good, 33.3% average), FW 22.2% (100% good), and DS 11.15 (100% good).

The data from this section are summarized in Table IV-4. It also includes the data on two parameters, which are monitored on-line by less than 3 utilities.

Table IV-4: Summary of Dutch and Belgian investigation on use and performance of on-line measurements at water utilities.

<table>
<thead>
<tr>
<th>Parameter monitored on-line</th>
<th>Number of utilities (N = 9)</th>
<th>Number of sites (N = 45)</th>
<th>Equipment reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Good</td>
<td>Average</td>
<td>Poor</td>
</tr>
<tr>
<td>Water flow rate</td>
<td>9 (100%)</td>
<td>33 (73.3%)</td>
<td>23 (69.7%)</td>
</tr>
<tr>
<td>Turbidity</td>
<td>9 (100%)</td>
<td>23 (51.1%)</td>
<td>19 (82.6%)</td>
</tr>
<tr>
<td>pH</td>
<td>8 (88.9%)</td>
<td>21 (46.7%)</td>
<td>15 (71.4%)</td>
</tr>
<tr>
<td>Water temperature</td>
<td>7 (77.8%)</td>
<td>22 (48.9%)</td>
<td>17 (77.3%)</td>
</tr>
<tr>
<td>Oxygen</td>
<td>6 (66.7%)</td>
<td>14 (31.1%)</td>
<td>10 (71.4%)</td>
</tr>
<tr>
<td>Conductivity</td>
<td>6 (66.7%)</td>
<td>11 (24.4%)</td>
<td>10 (90.9%)</td>
</tr>
<tr>
<td>Calcium/magnesium or Total hardness</td>
<td>4 (44.4%)</td>
<td>7 (15.6%)</td>
<td>1 (14.3%)</td>
</tr>
<tr>
<td>Biomonitors</td>
<td>4 (44.4%)</td>
<td>5 (11.1%)</td>
<td>0.5 (10.0%)</td>
</tr>
<tr>
<td>Particle count</td>
<td>3 (33.3%)</td>
<td>6 (13.3%)</td>
<td>5 (83.3%)</td>
</tr>
<tr>
<td>Spectral absorption</td>
<td>2 (22.2%)</td>
<td>3 (6.7%)</td>
<td>2 (66.7%)</td>
</tr>
<tr>
<td>Algae</td>
<td>1 (11.1%)</td>
<td>1 (2.2%)</td>
<td></td>
</tr>
</tbody>
</table>
d. Australian survey

Introduction
A survey was carried out to document Australian water utilities' current water quality monitoring status and anticipate their needs for state-of-the-art online monitoring technologies. A questionnaire (xls.file) was sent to 12 utilities, 8 of which (ca. 67%) returned a completed questionnaire. One water supply system has a utility to manage its catchments, bulk water supply and major distribution system and separate utilities (3) to manage distribution of the treated water to customers. Survey responses were received from the bulk water supply utility and two of the distribution utilities. These responses were combined into one water service provider giving 6 utilities overall for the survey assessment.

Questionnaire
Respondents were asked to indicate whether and how their utility monitored a list of parameters in various types of water. If analysis was by on-line instrumentation, the utility was asked how reliable the on-line equipment was. The parameter list included approximately 100 parameters from 7 main groups (e.g. General & Inorganic Parameters, Major Ions, Nutrients, Taste & Odour). Additional analytes were added to the survey questionnaire that was issued to the U.S., Belgium and Holland to reflect possible differences in Australian water quality issues. Some utilities also added analytes that did not appear on the survey but were monitored for. The 6 water types were 'stored raw water' (RW), 'ground water' (GW), 'surface water intake' (SW), 'water treatment - in process' (TP), 'water treatment - final water' (FW), and 'water in distribution system' (DS).

Results

Utility type
The results summarise responses from 6 water suppliers in total. In the case of the water supply that comprised a bulk water utility and separate distribution utilities the distribution utilities were handled as discrete entities when calculating the theoretical site numbers but the responses were combined as one utility in the result analysis.

The six utilities were a representative sample of water utilities for the major cities in Australia both in respect to their operational size and source water type. The utilities supplied from between 70,000 to approximately 4 million customers with water production ranging from 55 million cubic metres per year to 528 million cubic metres per year.

Out of the six water types, 4 utilities used stored raw water (RW; n = 4), 3 utilities used ground water (GW; n = 3). All utilities utilised source water intake (SW), treatment processes (TP), finished water (FW) and distribution systems (DS) (n= 6).
On-line Monitoring

Five water quality parameters, water flow, turbidity, pH, temperature and free chlorine were monitored on-line by all the utilities (n = 6) in at least one water type. The theoretical maximum of monitoring sites (the addition of all water types of all utilities) was 32. The actual number of monitoring sites reported for water flow, turbidity, pH, temperature and free chlorine was 21 (65.6% of the theoretical maximum), 18 (56.3% of the theoretical maximum), 15 (46.9% of the theoretical maximum), 15 (46.9% of the theoretical maximum) and 14 (43.8% of the theoretical maximum), sites respectively. The reliability of the on-line monitors was high for each of the analytes.

- **Water flow**: (76.2% ranked as good, 9.5% as average and 14.3% unspecified; n = 21 sites). All treatment processes (TP) were monitored on-line (n = 6) (reliability 66.6% good, 16.7% average and 16.7% unspecified). The other water types monitored on-line from most to least were: DS 66.7% (n = 6) (reliability 100% good), FW 66.7% (n = 6) (reliability 50% good, 50% unspecified), SW 50% (n = 6) (reliability 100% good), GW 66.7% (n = 3) (reliability 100% good) and RW 50.0% (n = 4) (reliability 50% good, 50% unspecified).

- **Turbidity**: (77.8% ranked as good, 5.6% as average, 1% as ‘poor’ and 11.1% unspecified; n = 18 sites). Of the water types, TP 83.3% (n = 6) (reliability 80% good, and 20% unspecified) and SW intake 83.3% (n = 6) (reliability 100% good) were analysed on-line the most. The other water types monitored on-line from most to least were: FW 66.7% (n = 6) (reliability 75% good, 25% unspecified), DS 33.3% (n = 6) (reliability 50% good, 50% average), GW 33.3% (n = 3) (reliability 100% good), and RW 25.0% (n = 4) (reliability 100% poor).

- **pH**: (60.0% ranked as good, 26.7% as average, 13.3% unspecified; n = 15 sites). All treatment processes (TP) were monitored on-line (n = 6) (reliability 66.7% good, 16.7% average and 16.7% unspecified). The other water types monitored on-line from most to least were: FW 50.0% (n = 6) (reliability 66.7% good, 33.3% unspecified), SW 50.0% (n = 6) (reliability 66.7% good, 33.3% unspecified), DS 33.3% (n = 6) (reliability 50% good, 50% average) and RW 25.0% (n = 4) (reliability 100% good).

- **Temperature**: (66.7% ranked as good, 13.3% as average and 20.0% unspecified; n = 15 sites). All treatment processes (TP) were monitored on-line (n = 6) (reliability 83.3% good, 16.7% unspecified). The other water types monitored on-line from most to least were: SW intake 50.0% (n = 6) (reliability 100.0% good), RW 50.0% (n = 4) (reliability 50% good, 50% average), FW 33.3% (n = 6) (reliability 50% good, 50% unspecified) and DS 33.3% (n = 6) (reliability 50% average, 50% unspecified).
• Free chlorine (78.6% ranked as good, 7.1% as average and 14.3% unspecified; n = 14 sites). All treatment processes (TP) were monitored on-line (n = 6) (reliability 83.3% good, 16.7% unspecified). The other water types monitored on-line from most to least were: FW 83.3% (n = 6) (reliability 80.0% good, 20% unspecified), DS 50.0% (n = 6) (reliability 66.7% good, 33.3% average).

Pressure, particle counts, conductivity and fluoride were monitored on-line by 5 of the utilities at a total of 6 (18.8% of the theoretical maximum number of sites), 9 (28.1% of the theoretical maximum number of sites) and 7 (21.9% of the theoretical maximum number of sites) sites, respectively. With the exception of pressure and conductivity, the performance of the on-line monitors for particle counts and fluoride were not considered to be very reliable.

• Pressure (100% ranked as good; n = 11 sites). Of the water types, TP 66.7% (n = 6) (reliability 100% good) was analysed on-line the most. The other water types monitored on-line from most to least were: RW 50.0% (n = 4) (reliability 100% good), DS 33.3% (n = 6) (reliability 100% good), GW 33.3% (n = 3) (reliability 100% good), SW intake 16.7% (n = 6) (reliability 100% good) and FW 16.7% (n = 6) (reliability 100% good).

• Conductivity (88.9% ranked as good, 11.1% as average; n = 9 sites). Of the water types, TP 66.7% (n = 6) (reliability 75% good, 25% average) was analysed on-line the most. The other water types monitored on-line from most to least were: SW intake 33.3% (n = 6) (reliability 100% good), FW 33.3% (n = 6) (reliability 100% good), RW 25.0% (n = 4) (reliability 100% good).

• Fluoride (33.3% ranked as good, 33.3% average, and 33.3% unspecified; n = 7 sites). Of the water types, TP 66.7% (n = 6) (reliability 50% good, 25% average, 25% unspecified) was analysed on-line the most. FW 50% (n = 6) (reliability 33.3% good, 33.3% average, 33.3% unspecified) was the only other water type monitored on-line.

• Particle count (33.3% ranked as good, 33.3% as average, 16.7% as poor and 16.7% as unspecified; n = 6 sites). Of the water types, TP 66.7% (n = 6) (reliability 25% good, 25% average, 25% poor, 25% unspecified) was analysed on-line the most. FW 16.7% (n = 6) (reliability 100% good) and DS 16.7% (n = 6) (reliability 100% average) were also monitored.

Total chlorine and dissolved oxygen were monitored on-line by 3 of the utilities at a total of 7 (21.9% of the theoretical maximum number of sites) and 3 (9.4% of the theoretical maximum number of sites) sites, respectively.

• Total chlorine (71.4% ranked as good, 28.6% as unspecified; n = 7 sites). Of the water types, TP 50% (n = 6) (reliability 66.7% good, 33.3% unspecified) and FW 50% (n = 6) (reliability 66.7% good, 33.3% unspecified) were analysed the most. DS 16.7% (n = 6) (reliability 100% good) was also monitored.

• Dissolved oxygen (33.3% ranked as good, 33.3% as average, 33.3% as poor; n = 3 sites). Of the water types, SW intake 33.3% (n = 6) (reliability 50% good, 50% poor) was monitored the most. RW 25.0% (n = 4) (reliability 100% average) was also monitored.

Two utilities monitored oxidation reduction potential (ORP) at a total of 2 sites (6.3% of the theoretical maximum number of sites). The reliability was 50% ranked as good and 50% unspecified (n = 2 sites). Of the water types TP 16.7% (n = 6) (reliability 100% good) and DS 16.7% (n = 6) (reliability 100% unspecified) were monitored.
The data from this section are summarized in Table IV-5. It also includes the data on parameters, which are monitored on-line infrequently but were reported by only one utility.

**Table IV-5: Summary of Australian investigation on use and performance of on-line measurements at water utilities.**

<table>
<thead>
<tr>
<th>Parameter monitored on-line</th>
<th>Number of utilities (n = 6)</th>
<th>Number of sites (n = 32)</th>
<th>Equipment reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Good</td>
<td>Average</td>
<td>Poor</td>
</tr>
<tr>
<td>Water flow</td>
<td>6 (100%)</td>
<td>16 (75.2%)</td>
<td>2 (9.5%)</td>
</tr>
<tr>
<td>Turbidity</td>
<td>6 (100%)</td>
<td>14 (77.8%)</td>
<td>1 (5.6%)</td>
</tr>
<tr>
<td>pH</td>
<td>6 (100%)</td>
<td>9 (60.0%)</td>
<td>4 (26.7%)</td>
</tr>
<tr>
<td>Temperature</td>
<td>6 (100%)</td>
<td>10 (66.7%)</td>
<td>2 (13.3%)</td>
</tr>
<tr>
<td>Free chlorine</td>
<td>6 (100%)</td>
<td>11 (78.6%)</td>
<td>1 (7.1%)</td>
</tr>
<tr>
<td>Pressure</td>
<td>5 (83%)</td>
<td>11 (100.0%)</td>
<td>1 (11.1%)</td>
</tr>
<tr>
<td>Conductivity</td>
<td>5 (83%)</td>
<td>9 (88.9%)</td>
<td>1 (11.1%)</td>
</tr>
<tr>
<td>Fluoride</td>
<td>5 (83%)</td>
<td>3 (42.9%)</td>
<td>2 (28.6%)</td>
</tr>
<tr>
<td>Particle count</td>
<td>5 (83%)</td>
<td>2 (33.3%)</td>
<td>1 (16.7%)</td>
</tr>
<tr>
<td>Total chlorine</td>
<td>3 (50%)</td>
<td>5 (71.4%)</td>
<td>2 (28.6%)</td>
</tr>
<tr>
<td>Dissolved oxygen</td>
<td>3 (50%)</td>
<td>1 (33.3%)</td>
<td>1 (33.3%)</td>
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<td>Oxidation reduction potential</td>
<td>2 (33%)</td>
<td>1 (50.0%)</td>
<td>1 (50.0%)</td>
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<td>True colour</td>
<td>1 (16.7%)</td>
<td>1 (3.1%)</td>
<td>1 (100.0%)</td>
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<td>Iron</td>
<td>1 (16.7%)</td>
<td>1 (3.1%)</td>
<td>1 (100.0%)</td>
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<tr>
<td>Manganese</td>
<td>1 (16.7%)</td>
<td>1 (3.1%)</td>
<td>1 (100.0%)</td>
</tr>
<tr>
<td>Biomonitor</td>
<td>1 (16.7%)</td>
<td>1 (3.1%)</td>
<td>1 (100.0%)</td>
</tr>
<tr>
<td>Spectral absorption</td>
<td>1 (16.7%)</td>
<td>1 (3.1%)</td>
<td>1 (100.0%)</td>
</tr>
<tr>
<td>Ammonium</td>
<td>1 (16.7%)</td>
<td>1 (3.1%)</td>
<td>1 (100.0%)</td>
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