# D5.4 Report on demand and challenges for miniaturised water monitoring technology in rivers and streams

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"Monitoring and management of flowing rain water in Baltic Sea catchment areas"

# 1 Introduction

Currently used water monitoring methods based on occasional samplings, manual methods in data management and limited use of costly continuous monitoring devices do not enable continuous surveillance of large geographical areas or water streams with diffuse load of pollutants. This report discusses some of the opportunities, challenges and bottlenecks of transition from existing water quality monitoring technologies to a new era of autonomous low-cost water monitoring systems.

Availability of methods for early detection, identification and characterization of pollution in natural flowing waters is currently limited due to the cost of the monitoring equipment, the need for frequent maintenance and the lack of efficient data mining tools. The cost of monitoring equipment puts limitations on the provision of high resolution data on diffuse and unidentified pollution sources. A need for low-cost high resolution monitoring solutions is obvious.

A possible solution for these problems is the development of low-cost autonomous, self-sufficient and maintenance free monitoring equipment that may be distributed in a large scale to increase the number of measurement points and consequently improve the resolution of water quality data. Alternatives to this approach may be advanced to air-borne advanced multi-wavelength monitoring (e.g. satellites, unmanned aerial vehicles or other moving objects in air) or autonomous underwater vehicles (AUV). Future advances in technology will probably enable all these solutions, resulting in a high quality surveillance system where data fusion from all these types of monitoring will be important.

The global demand for continuous water quality monitoring devices has been described in a more detailed manner in the D5.2 –report of the Baltic Flows -project.

# 2 Opportunities for miniaturized water quality monitoring technology

This section describes some of the emerging sensor technologies that have potential to advance the breakthrough of continuous in-situ measuring technologies in water monitoring. This list is not exhaustive, but it aims at giving insight into some opportunities new sensing technologies could provide to water monitoring applications. Those technologies that are currently most widely used have been described in the D5.2 report.

## 2.1 Ion sensitive field-effect transistors (ISFET)

Ion sensitive field-effect transistors (ISFETs) were introduced in the 1970s and have since received tremendous attention in the research field and are also commercially available as pH meters. The structure of the original ISFET is based on the metal oxide semiconductor field-effect transistors (MOSFETS). The gate of the MOSFET is removed and the underlying oxide is used for detection of hydrogen ions in the solution. The detection is based on the change in the surface charge, which creates a potential change across the solution, which is referred against the reference electrode immersed into the solution. This modulates the transistor channel conductance and subsequently the drain current.

Since the ISFET is thus able to transform a chemical event directly to electrically measurable signal, it does not require labeling or bulky optical detectors unlike light-based methods. It enables the exploitation of the benefits of modern semiconductor processes and piggybacks on the unparalleled development of it. The integrated chip technology has not only a very low power consumption, but it is also low-cost, scalable and has multiplexing abilities.  An exemplary of this multiplexing ability is the semiconductor sequencing, where local pH changes are measured from DNA hybridization event known as the Ion Torrent Technology.

Ion specific sensing membranes enable the detection of various metal ions e.g. for environmental monitoring purposes as well as other chemical compounds. Today, practically all ions detected potentiometrically have been demonstrated to be applicable also with the ISFETs. Biosensors are one of the most recent trends in ISFET based sensor development. The driving idea has been to use biomolecules and biological systems to create highly specific and sensitive sensors. A biosensor comprises of a biological recognition element and physico-chemical transducer. One promising method for creating a specific biosensor is to attach a biologically sensitive material to the transducer. Such sensing molecules include e.g. enzymes, antibodies, antigens, proteins and nucleic acids. The recognition element translates the information from the chemical/biological domain to physical/chemical signal. Biosensors are portable and simple-to-use. They are high specificity analytical tools compatible with data-processing technologies. They show great promise and could be used as applications in various fields, such as environmental monitoring, pharmacy, health care, food and agricultural product processing.

## 2.2 MEMS Microelectrode Array Sensors

Microelectromechanical systems (MEMS) are integrated sensors or systems of devices that combine electrical and mechanical components. Miniature-sized mechanical elements are fabricated by micromachining techniques from silicon wafers and assembled with microelectronic components to form for example microsensors and microengines. The technology allows for fabrication of large systems of MEMS devices, which individually perform simple tasks, but jointly perform complicated functions. MEMS allow sensing, controlling, and activating physical and chemical processes on a miniature scale. MEMS array sensors provide possibilities for multi-analyte detection and a robust method for in-situ monitoring.

MEMS are close to electronic components in manufacturing processes and can be built up from silicon, ceramics, carbon or other different materials with material deposition in clean rooms. An important feature potentially provided by MEMS built up with PZT ceramic components is the generation of voltage when applied by mechanical forces, or temperature gradients. Applications with these kinds of materials as sensors of force, temperature or low power electrical generators may be important for monitoring sensors.

The current MEMS technology spans from very simple low-cost and high-volume products like audio transducers, time base crystals and radio filters. New fields of applications have also been launched, where MEMS materials are used as energy generators, molecular scales, sensors for acceleration, physical environment parameters or as passive communication links. Combinations of MEMS and electronic functionality in small-size packages are currently providing added sensing features both in professional equipment and in mass market mobile phones in sensor functions (e.g. gyros for 3D navigation and acceleration measurements). The entrance of MEMS into mass markets has considerably lowered their price.

Research activities within this field using MEMS components as electronic scales together with micromechanics and microchemistry results in new precision chemical or molecular sensors that are attractive in size, price and power consumption.

## 2.3 Microwave sensors

Microwave sensing is a new and emerging technology, which has been successfully used as a sensing method for various industrial applications including water level and quality measurements, material moisture content and medical industry. There are possibilities to apply microwave sensors to a broad range of application. For example microwave sensors have potential in monitoring wastewater nutrients, such as phosphate and nitrate. Microwave sensors could provide many advantages in real-time sensing, compared to other, traditional sensor techniques. Microwave based analyzes give continuous and instantaneous measurement, when a material flows through without the need for significant pre-processing and providing direct sample measurement. In addition to specific measurements, microwave sensors could function as a low-cost solution, which is sensitive for several compounds in the water. Measurement is based in the unique interaction of the measured compound or material with electromagnetic waves. Interaction changes the permittivity of the compound. Composition of the sample can be linked to the variation of the frequency and transmittance caused by microwaves.

## 2.4 Monitoring software, networking and energy supply for miniaturized monitoring

Assuming a very large number of low power wireless sensors with short range radio links are deployed, it will be necessary to create systems for identities, communication cooperation for transport of measurement data and more advanced concepts on how to manage large amounts of data types (sensor values). Recently developed standards are approaching these problems with larger address schedules like IPv6 together with adopted internet communication and packet routing algorithms. Since autonomous wireless sensors are energy limited, power cycling concepts are developed to reduce power consumption. This is a field of research where many different methods and solutions are discussed and applied, since adoptions are strongly dependent on the application requirements of the planned sensor network. The flowing water monitoring applications may primarily require emphasis on features such as a wide geographical coverage, low density mesh network array with low sampling frequencies, provided that data values are within certain limits. Low energy sensing and communication features are important, and may have a large impact on software design and configurations.

Common methods to implement low energy consumption such as extensively duty cycling of processing and communication services together with requirements for reliable communication services puts difficult requirements on total system software design. The combination of today's state of the art solutions with sensor nodes and short range radio links, communicating with IPv6/6lowPan mesh network protocols and a control CPU powered on only 2-3% of the total time is an interesting challenge.

### 2.4.1 Data collection, surveillance and networking through Internet

Larger land areas covered with autonomous short range wireless sensor networks monitoring water parameters will have some theoretical and practical limitations with regards to the suitable locations of data access points or gateways. These uplink access points or gateways linking the data to an online data cloud need to be powerful node gateways, which require continuous energy supply. Data from the sensor network is received and reformatted before it is forwarded to the online computers and databases. Additional communication protocols and procedures together with security firewalls and encryption have to be applied to preserve data integrity before an online connection is established. Access methods may be GSM/4G, WiFi, long range radio link or satellite link, depending upon sensor network location conditions and placement.

Different and more unusual approaches have also been studied, such as Data Mules or manual collection of larger amounts of buffered or stored data from access points. These solutions are suitable in some situations where data does not need to be delivered in a certain timeframe. This type of data collection can be compared with the early days of bottle-mail.

# 3 Challenges and bottlenecks in the development of miniaturized sensor technologies in the context of rivers and streams

Despite the fast uptake of new measuring technologies in many applications, such as monitoring of the human body and indoor air quality measurements, the sensors and technologies used in continuous in-situ water quality monitoring have not significantly changed over the last 15 years. The reasons for this are partly related to limited financial resources for water monitoring purposes and to the lack of links between high-end sensor technology experts and water monitoring experts. However, there are some technical challenges, specially affecting measurements in the context of rivers, streams and ditches that would need to be resolved.

## 3.1 Energy supply options and management

The largest challenge when considering the design of a wireless networked water monitoring system is to provide a good solution for the power supply. It is challenging to harvest and store sufficient energy for each node in the system to remain active and provide the necessary services for the data chain or network for area monitoring. The more energy can be harvested, the more functionality can be implemented in each sensor node. Sufficient power supply also enables the use of several sensor types and more frequent data logging. In addition, more complex software systems and better radio performance can be achieved. Like in all wireless networks, the balance between the available energy and performance over time is the main issue. Since electronics and software are not the biggest bottlenecks in creating good operational networks, the main challenges are in the energy harvesting power systems and physical sensor areas.

Although the earlier mentioned continuously ongoing market introduction of smaller, smarter and less power hungry components is a fact, there are a number of reasons, why the focus should be on energy management and in creating power autonomous sensors. Energy for communication and conversion of physical environmental parameters are always needed, and some physical parameter conversion methods are more power consuming than the electronics used for A/D conversion of data and communication links (example such as heaters in gas sensors). Efforts should therefore be targeted at methods, which would solve the problem of harvesting energy from the local environment or physical conditions. Intermittent energy sources like sunshine, water flow, wind or vibrations have always been sources of energy production in large scale power plants. But when these well-known methods have to be applied in the micro scale, new interesting problems appear. This intermittent energy is harvested using very small and low cost harvesters/generators, and the energy needs to be accumulated and stored in capacitors or rechargeable batteries. Common harvester generator methods are mechanical (rotating or moving coil generators or piezo elements), solar cells, wind generators, thermal difference (TEG or Peltier), but other more exotic solutions are available – such as low-decay nuclear energy cells or nanotube storages.

Water sensing applications working with continuous water flow would benefit from harnessing energy from the water flow. Thermal energy could also be a promising solution to provide for the energy needs of these devices. However, if no regular water flow is expected, the system should have some alternative energy sources. Especially if sensor conversion methods are using high energy levels, local energy storage or batteries must be used. Currently there is no established commercial measuring devices that would get their energy directly from flowing water. One bottleneck for developing such devices is the absence of mass volume applications and consequently, lack of funding for the development. Energy harvesting from the flow is not necessary in industrial applications and there are no measurement products that would need to harvest energy from flowing water in commercial markets either.

## 3.2 Encapsulation of the sensors

Flowing water is a challenging environment to measure. The device must endure mechanical stress and temperature variations (including frost) and the electrical parts should be encapsulated in a way that water cannot harm the electronics. In addition, the device should be able to operate for extended periods without maintenance. Fooling of the sensors is another problem. All devices currently used in field conditions have some kind of a cleaning system. The problem is that the cleaning systems increase the size, price and the energy consumption of the device.

One of the bottlenecks for resolving these technical challenges is that companies or research organizations developing novel sensor technologies have very good expertise in the sensing technology, but often lack expertise that would allow them to overcome problems in harnessing the sensing element into use in environmental conditions, in the form of a complete monitoring device that can enter the markets. Thus, co-operation between sensor developers and companies that can use the sensors in their monitoring solutions would need to be increased.

## Literature

Aksunera, N., Basarana, B., Hendena, E., Yilmazb, I., Cukurovalic, A. (2011): *A sensitive and selective fluorescent sensor for the determination of mercury (II) based on a novel triazine-thione derivative.* Dyes and Pigments 88, 143–148

Bergvald, P. 2003. Thirty years of ISFETOLOGY. *What happened in the past 30 years and what may happen in the next 30 years.* Sensors and Actuators B 88 (2003) 1-20.

Jimenez-Jorquera, C., Orozco, J., Baldi, A. 2010. *ISFET Based Microsensors for Environmental Monitoring*. Sensors 10 (2010) 61-83.

Leonard, P., Hearty, S., Brennan, J., Dunne, L., Quinn, J., Chakraborty, T., O'Kennedy, R. 2003. *Advances in biosensors for detection of pathogens in food and water*. Enzyme and Microbial Technology 32 (2002) 3-13.

Lindsey, S. 2012. *Biochemistry and Semiconductor Electronics – The next Big Hit for Silicon?* J Phys Condens Matter 25:16 (2012) 164201.

Mukhopahyah S.C & Mason A. (2013): Smart Sensors for real- time water quality monitoring, Springer Heidelberg New York Dordrecht London: ISBN 978-3-642-37006-9

Schöning. M. & Poghossian, A. 2002. *Recent advances in biologically sensitive field-effect transistors (BioFETs)*. Analyst 127 (2012) 1137-1151.

Zhang, X.B., Guo C.C, Li Z.Z., Guo-L., Shen G. L: and Yu R.Q (2002): *An optical fiber chemical sensor for mercury ions based on a porphyrin dimer*. Analytical Chemistry 74, 821–825