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An Ghníomhaireacht um Chaomhnú Comhshaoil

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SmartCoast Project – Smart Water Quality Monitoring System

SSTI
Strategy for Science, Technology and Innovation

Comhshaol, Oidhreacht agus Rialtas Áitiúil
Environment, Heritage and Local Government

Marine Institute/Environmental Protection Agency Partnership: Advanced Technologies for Monitoring Water Quality

STRIVE Programme 2007–2013

SmartCoast Project – Smart Water Quality Monitoring System

(AT-04-01-06)

Synthesis Report

End of Project Report available for download on http://erc.epa.ie/safer/reports

Prepared for the Marine Institute and the Environmental Protection Agency

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DISCLAIMER

The EPA STRIVE Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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FOREWORD

The Environmental Protection Agency (EPA) and the Marine Institute entered a strategic partnership agreement in July 2005 in the broad areas of Environmental Technologies and Water Quality Monitoring. The aim was to catalyse an innovative programme of environmental technology research to underpin the development of the Smart Green Economy.

The specific aims of the partnership were:

- To build national research and innovation capacity in the area of water quality monitoring, particularly in respect to implementation of the Water Framework Directive

- To provide technological support for the sustainable development of aquatic/marine resources, and

- To support the creation of new industrial capabilities in these areas.

An initial core suite of three-year research projects was funded with the objective of forming a consortium of national capabilities to address market opportunities associated with marine and environmental technology development. A review of the projects and the overall programmatic approach indicates that performance and achievement of strategic objectives are broadly in line with those established at the outset.

In addition, as the projects evolved, the ability to test and demonstrate prototype and pre-operational environmental sensors and communications technology in the field became apparent. The SmartBay pilot project emerged as a response to this and was developed jointly by the Marine Institute and the EPA under the initial collaborative agreement. The objective is to develop SmartBay (in Galway Bay) as a strategically positioned and uniquely located marine research, test and demonstration platform, with a reputation for leading-edge technologies for global markets and the development of innovative solutions to important environmental questions. The SmartBay project is advancing with the input of a wide range of agencies, researchers, industry and end-users.

The EPA and the Marine Institute have agreed a further collaborative research programme for the period up to 2011. Its main focus will be to support the implementation of a number of EU Directives (Water Framework, Strategic Environmental Assessment, Marine Framework and Bathing Water) as well as national efforts in response to the EU Environmental Technologies Action Plan (ETAP).

In this research report, we publish the findings of one of the projects on water monitoring systems. The report presents some exciting results in terms of the quality of the research, the expertise and capability developed from the agencies' shared investment.

In the current economic climate, co-operation between research funders is more important than ever to maximise the impact and benefits from investments in research. The partnership approach adopted by the EPA and the Marine Institute in relation to the research presented in this report is an excellent example of such co-operation and is a vital support in the development of Ireland's Smart Green Economy. This co-operation has led not only to the development of critical national research capacities and capabilities, but will also help position Ireland as a leader in developing innovative technological solutions for the environmental and marine areas and to take advantage of one of the fastest growing markets in Europe.

Dr Mary Kelly
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Executive Summary

1 Background

Environmental and water quality monitoring are key to measuring and understanding the chemical and biological quality of water and for taking reactive remedial action. Over the coming years, monitoring of waterbodies will increase within Europe, in order to comply with the requirements of the Water Framework Directive (WFD, Council Directive 2000/60/EC), and globally, owing to pressure from climate change. The establishment of high-quality long-term monitoring programmes is regarded as essential if the implementation of the WFD is to be effective[1].

2 Project Aims

The SmartCoast Project, co-funded by the Marine Institute and the Environmental Protection Agency (EPA) (Grant Aid Agreement No. AT-04-01-06), aimed to develop novel monitoring technologies that can continuously collect data on water quality in lakes, rivers and estuaries. The objective of such technology is to transmit information via wireless links directly to a computer, delivering detailed data at levels that would otherwise be difficult, if not impossible, to achieve. An objective of this project was to build capacity in the area of environmental monitoring in Ireland. Thus, a unique consortium of partners was established, comprising two of the most relevant university research centres (the National Centre for Sensor Research (NCSR), Dublin City University, and Tyndall National Institute (TNI), University College Cork), together with an SME (small and medium-sized enterprise) prototype development company (The National Microelectronics Applications Centre (MAC)), a specialist SME already operating in the water quality monitoring area (Marine Informatics (MaInf)) and two end-users (the Marine Institute and the South West Regional Authority (SWRA)), in a focused programme of research contributing to establishing Ireland's reputation as a location for developing futuristic solutions to water quality monitoring issues. The project aimed to develop novel sensor technologies for water quality parameters and, combined with existing sensor technologies, build and test a sensor network to study continuous water monitoring.

1. Grath, J., Ward, R., Scheidleder, A. and Quevauliller, P., 2007. Report on EU guidance on groundwater monitoring developed under the common implementation strategy of the Water Framework Directive. *Journal of Environmental Monitoring* **9:** 1162–1175.

3 Key Findings

As part of the project, new sensors for measuring dissolved oxygen and phosphate were developed and tested in the field. Communication and sensor technology were integrated in a novel manner and this led to a phased testing and demonstration of the research. The SmartCoast team showcased the real-time water quality monitoring technology, developed over the course of the research, in the River Lee in Cork in May 2008. The technology demonstration involved the integration of a group of water quality sensors into a distributed communication network, through interfacing them with the PSoC plug-and-play system, with ZigBee® telemetry, capable of transmitting the data to the SmartCoast server, which processed the data for transmission to the web. The demonstration of a truly heterogeneous water quality monitoring networked system was the first of its kind in Ireland and showed how data could be collected from a number of locations and viewed in real or near real-time. The results of the demonstration were available live on the project website (http://www.smartcoast.net). This project enabled the establishment of a critical mass of research on environmental monitoring in Ireland and also amassed valuable knowledge from the process (see End of Project Report available for download on http://erc.epa.ie/safer/reports).

4 Future Activities

This research programme has led to a small-scale long-term monitoring research project beginning in early 2009, where some sensors will be deployed at a number of locations in the River Lee, Co. Cork. Using a variety of deployment platforms and communications tools, data from this test and demonstration site will be collected for 12 months and will be presented on a web page. This type of research and demonstration approach is necessary to enable future novel devices to be tested in the field with suitable data handling and communications resources. More such demonstrations are needed, together with increased resources, in order to see monitoring technologies commercialised.

The use of *in-situ* sensors capable of continuous sampling of parameters offers the potential to reduce costs, as well as providing more up-to-date information and better coverage, revealing long-term trends in fluctuations of pollutant concentrations[2]. The ideal monitoring system of the near future might consist of a network of sensors deployed at key locations, capable of autonomous operation in the field for a year or more[1]. The data from the monitors will be communicated by wireless technology for processing and interpretation. Although some elements of this ideal system are in place, ongoing research and development is required in several areas relating to both sensor development and field testing.

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2. Greenwood, R., Webster, J. and Regan, F., 2008. *Sustainable Water: Chemical Science Priorities*, RSC Report http://www.rsc.org/images/Chap4_tcm18-108474.pdf.

1 Introduction

Environmental and water quality monitoring are key to measuring and understanding the chemical and biological quality of water and for taking reactive remedial action. Monitoring of waterbodies will increase over the coming years, within Europe in response to the needs of the Water Framework Directive (WFD), and globally, owing to pressure from climate change (Greenwood *et al.,* 2008). Monitoring at river basin level for the WFD is a significant financial burden when using conventional sampling and laboratory-based techniques, but sensors offer the potential to considerably reduce these costs, as well as providing more useful, continuous monitoring capabilities. Traditional environmental and water quality monitoring is a means of providing information on the status of the natural environment and of detecting long-term changes resulting from anthropogenic activities, but does not normally allow for the detection of occasional events (Greenwood *et al.,* 2008).

Despite the increasing range and diversity of techniques currently available, continuous on-line *in-situ* measurement systems remain largely limited by environmental factors, interferences, fouling problems, cost, power requirements, short lifetime and the need for chemical reagents, as well as frequent calibrations. While the measurement and detection of environmental pollutants can be successful under laboratory conditions, continuous monitoring remains the most challenging aspect of environmental sensing.

The area of wireless sensing, particularly the concept of wireless networked sensors, is fast becoming one of the most dynamic and important areas of multidisciplinary research. The ideal monitoring system of the near future might consist of a network of sensors deployed at key locations capable of autonomous operation in the field for perhaps a year or more (Grath *et al.,* 2007). In addition to basic water quality parameters, such as dissolved oxygen (DO), conductivity, pH, turbidity and nutrient status, new developments will allow sensitive and specific monitoring for a range of organic contaminants such as pesticides or chlorinated hydrocarbons. In addition, toxicity monitoring will be used as a screening tool, albeit non-specific, for detecting the advent of unsatisfactory water quality. The SmartCoast Project was launched in June 2005 and represented an important building block in the realisation of an 'environmental nervous system' composed of multiple sensing nodes deployed as a 'sensor-net' capable of monitoring the spatial and temporal distribution of important environmental target species as prioritised in the WFD. For full project details see End of Project Report which is available for download from http://erc.epa.ie/safer/reports.

1.1 Objectives

The objective of the SmartCoast Project (a partnership between Dublin City University (DCU), the Marine Institute, Tyndall National Institute (TNI), The National Microelectronics Applications Centre (MAC), the South West Regional Authority (SWRA) and Marine Informatics (MaInf)) was to produce an innovative, intelligent, autonomous data collection system to meet the requirements of the WFD, as there does not appear to be any current system in place that fulfils all the requirements of the Directive. The project is a flagship one, showcasing the capabilities of indigenous high-tech industries and institutes, and should be marketable Europe-wide to the various agencies responsible for water quality management that are affected by the WFD guidelines.

A number of research tasks were identified, including:

- Specification of the user requirements
- Research into new sensors
- Deployment of sensors currently available
- Integration of sensors with new plug-and-play platforms
- Development of a smart water platform

- Field evaluation of the technology at various stages of the process, and
- Demonstration of the technology.

The project tasks were designed, individually and in combination, with work packages led by the various project partners, as directed in the project plan, to address the following general objectives:

1. Development of new sensors
2. Collation of market analysis studies of direct relevance to the sensors
3. Reduction in sensor cost and improvement in field deployment lifetime of sensors
4. Data collection in real time
5. Sensor network and wireless sensor capability, and
6. Validation of developed sensor performance and enabling deployment, installation and maintenance of units without skilled labour.

2 Background to the Project

SmartCoast was a 3-year applied R&D Project, co-funded by the Marine Institute and the Environmental Protection Agency (EPA) (Grant Aid Agreement No. AT-04-01-06), which was aimed at developing novel sensing technologies that can continuously collect data on water quality in lakes, rivers and estuaries and transmit this information *via* wireless links directly to a computer, delivering detailed data at levels that would otherwise be difficult, if not impossible, to achieve. In 2003, the Marine Institute commissioned a review of and feasibility study on requirements, current developments and potential innovations in respect of sensor systems to support the implementation of the WFD in freshwater catchments. This was carried out by TNI and its findings included the following.

Real-time sensing of water has a number of common limitations which are distinctive of the technology. Sensor drift is one of the most serious impairments of chemical and biochemical sensors. Despite efforts to improve long-term stability, manufacturers have yet to release sensors that are not affected by some degree of drift. One of the major challenges is to be able to systematically reduce the dimensionality of the incoming data, while preserving all relevant information. So far there has been no systematic approach to the problem of data reprocessing and analysis. It seems that the choice of suitable output (desorption signal, baseline, transient/maximum response, etc.) and analytical protocol is often the result of trial and error, largely based on personal intuition or experience. Unfortunately this is a time-consuming process, which requires highly skilled personnel. The adequate validation of environmental sensing systems is rarely carried out and therefore results are not always meaningful. The main reason for this is that validation takes too much time and money for a single developer to bear full responsibility for the task. In practice, lack of validation significantly hampers implementation. SmartCoast aimed to deploy its sensor network to demonstrate to interested parties the benefits associated with continuous *in-situ* monitoring.

3 Engagement with Users

3.1 Introduction to User Group Requirements

In order to design a monitoring system of value, the SmartCoast Project established a user group as part of its information gathering process. Initially, the project identified all relevant public sector organisations and invited them to attend a project briefing meeting to create a relationship between the user group and the project. The SmartCoast Project team engaged in a series of meetings with the River Basin Districts (RBDs) in 2006 and 2007, which took the form of briefings and discussions that allowed a two-way flow of information.

3.2 User Group Needs

The following is a list of needs that were identified by users of water monitoring systems in relation to developing an ideal monitoring system:

- Innovation
- Variable monitoring frequencies
- A multi-sensor solution
- Data integrity and presentation
- Cost-effective
- Real-time data collection/alarms
- Portability
- Scalable on demand, and
- Reliability/Ruggedness.

3.3 Recommendations

Owing to SmartCoast and other related investments in environmental sensing R&D, Ireland is well positioned relative to other countries, even the US, in terms of expertise. Therefore, there is a real opportunity for Ireland to make critical contributions in this area. A number of recommendations arose from discussions that took place during a SmartCoast workshop, and it is important that these are given due consideration for future approaches to effective water monitoring technologies, systems and programmes.

3.3.1 Recommendation No. 1: Partnerships

It was recommended that partnerships should be built between academia, agencies and end-users that will lead to long-term capability and trust in the technology. Similarly, agencies must have a stake in the technology development process and thus in the quality of the data.

3.3.2 Recommendation No. 2: Demonstrations

Valuable reference data for research prototypes can be obtained by using off-the-shelf commercial systems at certain test deployment sites. The latter will also provide data for environmental systems research. It was recommended that demonstrations must be led by the end-user.

3.3.3 Recommendation No. 3: Other parameters

Fundamental research needs to be continued in areas such as biological contaminants and nutrient species.

3.3.4 Recommendation No. 4: Sustainability

It is recommended that long-term funding is given to enable further research into new technologies and effective technology transfer to small and medium-sized enterprises (SMEs). There is a need for the establishment of a small number of reference/test sites at which there is an infrastructure to plug devices into to enable continual development and testing of new systems/devices.

4 Overview of SmartCoast Platform

The SmartCoast platform covers all aspects of user requirements for the viewing of sensor data by end-users using a standard web browser as shown in Fig. 4.1.

4.1 System Architecture Requirements

A number of important decisions were taken early in the project that influenced the overall system design approach taken to design the SmartCoast platform. These included:

- All communications with the sensors to be wireless (as opposed to wired or manual display/keypad interface).
- A variety of sensors would be deployed at a monitoring site and sensors could easily be added and removed when required, i.e. for seasonal monitoring purposes.
- The sensor nodes would be designed for ease of maintenance and deployment.
- While 'real-time' monitoring is not a strong requirement of the WFD, it was agreed that alarm alerts on measurement thresholds, such as pollution alerts, would be a critical component of the system and would add to the success of the project.
- Where possible, the design adheres to industry standards to ensure future-proof design and compatibility of the system with other possible available solutions.

4.2 Proposed System Solution

An important aspect of the overall solution was the decision that each individual sensor would have its own low-power radio capable of communicating from 75 to 100 m (unobstructed space) using the IEEE

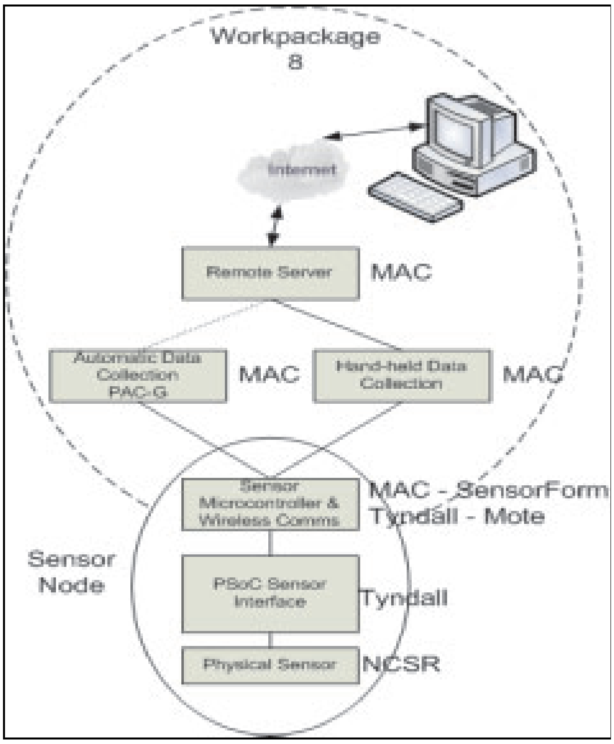

Figure 4.1. Outline of the scope of work undertaken in the design of the SmartCoast platform. (MAC, National Microelectronics Applications Centre; NCSR, National Centre for Sensor Research.)

802.15.4 ZigBee® data communications standard and operating in the license-free 2.4 GHz spread-spectrum radio band. ZigBee® is a low-power wireless networking technology that is targeted at sensing, monitoring and control applications.

4.3 System Architecture Design

Based on the user requirements and the choice of a wireless sensor interface, the following two system architecture options were designed:

1. ***Local area network ('drive-by') for local monitoring of sensors*** A low-cost, low-power sensor support network that requires manual extraction of the data from the sensors by a hand-held wireless device.

2. ***Wide area network for 'real-time' monitoring and control of sensors*** A low-cost, low-power sensor support network that facilitates real-time monitoring of sensors for sensor measurement, alarm alerts and fast data reporting.

4.3.1 Local area network ('drive-by') for sensor monitoring

The main features of the local area network, shown in Fig. 4.2, include:

1. Each sensor unit shuts off ZigBee® communications to conserve power and only wakes up periodically to check if a 'parent' hand-held device is present. This period of sleep/wake-up is programmable from 'always-on' to once every few minutes. The recommended period is every 60 s.

2. A standard off-the-shelf personal digital assistant (PDA) (such as a DELL Axim X51) is used as the hand-held device and will have a ZigBee® radio unit connected. It will include a standard Windows operating system with full processing and display facilities.

3. A router node is used to extend the operating range of a network and also to enable a mesh network to be formed.

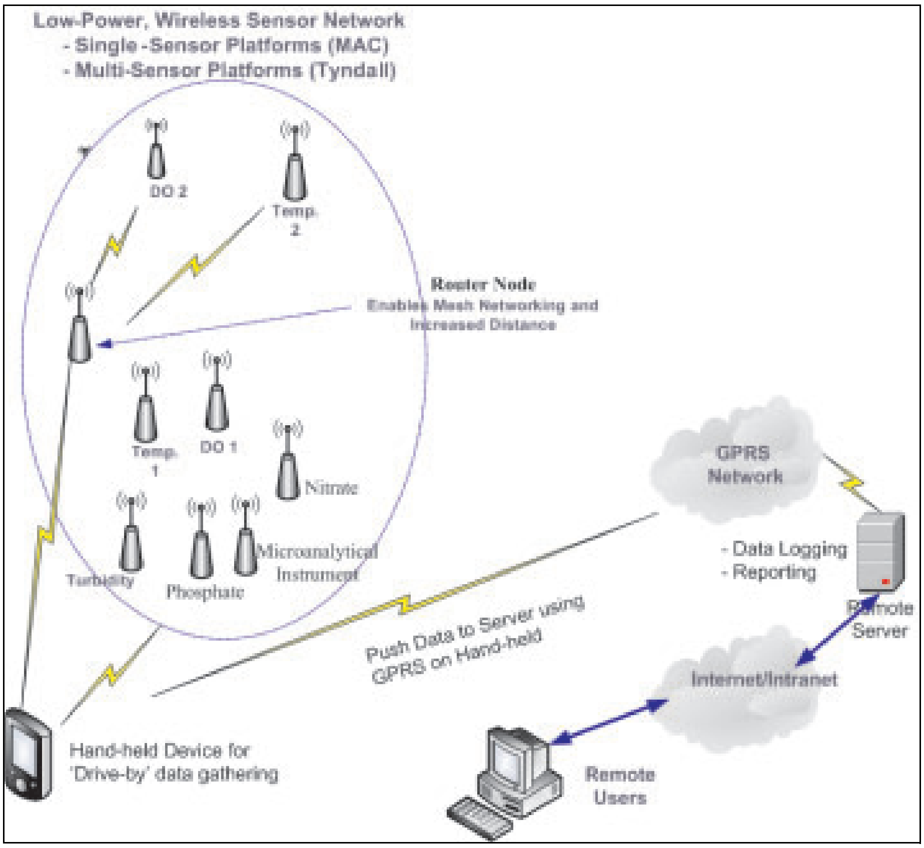

Figure 4.2. Sensor local area network. (DO, dissolved oxygen; GPRS, general packet radio service; MAC, National Microelectronics Applications Centre.)

4. Each installation (site) network configuration is pre-programmed into the hand-held device to enable ease of identification of the sensor network at this site and ensure that all sensors located on the site are accounted for when read by the hand-held PDA.

5. Sensor monitoring data, alarm data and unit status are uploaded to the hand-held device. It will also be possible to download new monitoring conditions to the sensor, such as frequency of sensor monitoring, as well as real-time clock synchronisation and wake-up frequency.

6. The hand-held device is capable of displaying individual sensor monitoring data and any alarm data generated.

7. It is possible to download new updated software release versions to each sensor unit from the hand-held device. This feature however will not be part of this development.

8. Uploaded data files stored on the unit will have a date/time stamp of upload.

9. It is possible to upload the data to a remote office personal computer or server *via* an optional general packet radio service (GPRS) connection to the hand-held device or manually by simply plugging the PDA into its cradle when back in the office and selecting the upload button.

4.3.2 Wide area network for real-time monitoring and control of sensors

The wide area network will provide a real-time monitoring and control facility for each sensor network or site. To enable this to happen, a programmable access controller – gateway (PAC-G) is used as a gateway for the sensor network to a remote (or local on-site) server. Initially, this is a GPRS connection but other wireless options would also be possible, such as WiMax and satellite. This network configuration is shown in Fig. 4.3.

The main features of the wide area network, shown in Fig. 4.3, include:

1. The PAC-G will continuously monitor the ZigBee® sensor network to ensure all devices are operational and will log any unit not communicating.

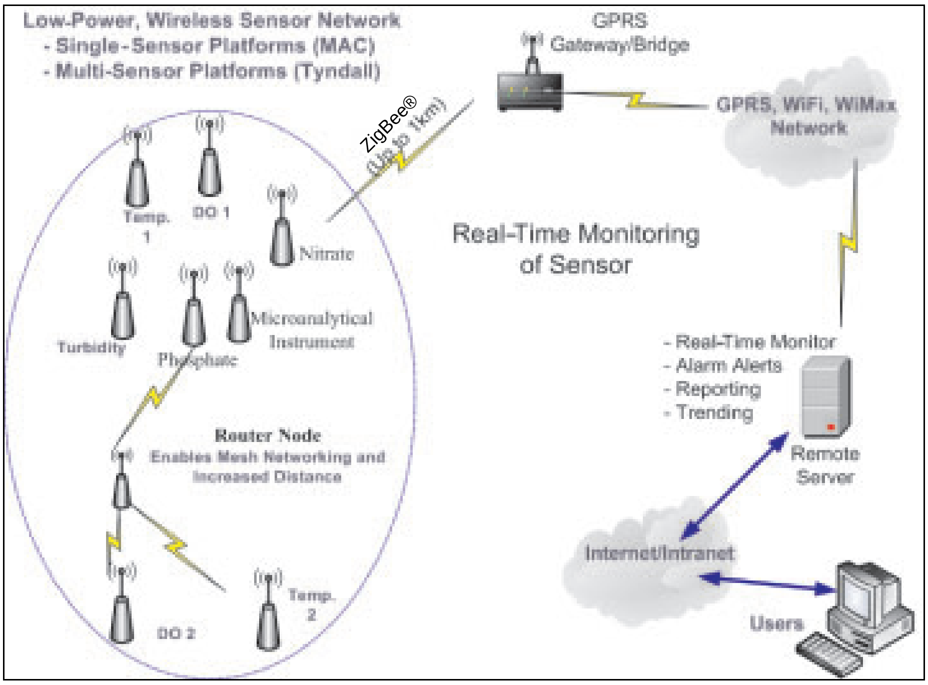

Figure 4.3. Wide area network of sensors. (DO, dissolved oxygen; GPRS, general packet radio service; MAC, National Microelectronics Applications Centre.)

2. Sensors will only communicate with the PAC-G when it has data to send or at a pre-programmed interval, such as daily, to check if there are any parameter monitoring changes requested, such as increased frequency of sampling. This extended sleep time (not having to wake-up every 60 s to see if a 'parent' device is there) of the sensors will assist in minimising power used on sensor units.
3. The network range can be expanded using a router node that will also enable mesh networking.
4. The frequency at which sensors take sensor readings is remotely programmable and will range from minutes to hours.
5. Sensors will immediately upload any monitoring data and the unit status to the PAC-G.
6. The PAC-G first stores the data and then forwards them to a remote server *via* the GPRS connection at pre-programmed intervals, e.g. once every 24 h.
7. Any sensor alarm data are transmitted immediately by the PAC-G to the remote server, i.e. when a sensor measurement threshold is breached, such as a pollution level.
8. All data are retained by the PAC-G until passed on to the server, so in the event of a server failure no data are lost.
9. All sensor monitoring requirements and alarm thresholds can be changed remotely.
10. New release versions of the application for sensor monitoring can be downloaded remotely from a central server *via* the PAC-G; no data analysis is performed by the PAC-G.

5 New Sensors Developed as Part of SmartCoast

While most of the sensors used for the project were off-the-shelf devices, one element of the research involved the development of novel sensors for two important water quality parameters. Building on existing technologies in the National Centre for Sensor Research (NCSR), a phosphate microfluidic device and a DO sensing probe were developed.

5.1 Phosphate Sensor

A field-deployable system for long-term monitoring of phosphate levels (see Fig. 5.1) in natural waters was developed, incorporating sampling, pumping, reagent and waste storage, optical detection and wireless communication in a robust and portable device. The phosphate sensor is based on the yellow vanadomolybdophosphoric method, which is a simple colorimetric technique that involves the formation of vanadomolybdophosphoric acid when a phosphate-containing sample is mixed in a 1:1 ratio with an acidic reagent containing ammonium molybdate and ammonium metavanadate. The resulting solution is yellow and absorbs strongly below 400 nm. The measured absorbance of the resulting yellow solution is used to determine the concentration of phosphate in the original sample (Bowden *et al.*, 2002; Bowden and Diamond, 2003). The phosphate sensor system combines microfluidic technology, a low-powered pumping system, sensitive colorimetric detection and wireless communications into an autonomous field-deployable device. The device can operate autonomously for 7 days on a single rechargeable 12 V battery. The sensor currently has a limit of detection of 0.3 mg/l and a linear dynamic range between 0 mg/l and 20 mg/l. At current sampling rates, it is possible to make 48 measurements a day with a reagent consumption of less than 30 ml/month.

The agreed sensor design criteria for the NCSR-developed phosphate sensor are shown in Table 5.1. The table outlines the objectives that were identified for the phosphate sensor developed during this project, and also shows how each of the specified objectives has been achieved.

The analyser platform is being further developed through Enterprise Ireland grants. The goal is to get the cost of the phosphate system down to €200 – an order of magnitude reduction in cost.

5.2 Dissolved Oxygen Sensor

The SmartCoast Project involved the development of a sensor (see Fig. 5.2) for monitoring DO in the aquatic

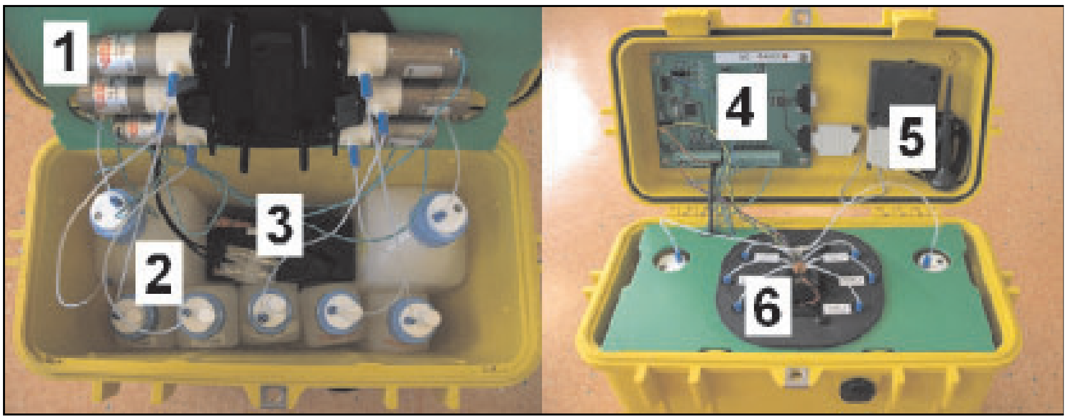

Figure 5.1. Fully assembled system. Visible components include solenoid pumps (1), fluid storage bottles (2), battery (3), control and memory board (4), GSM modem and aerial (5), and microfluidic chip/detector assembly (6).

Table 5.1. Summary of phosphate sensor design criteria.

Item	Objective	Current status
Sensitivity	Low µg/l	300 µg/l
Power consumption	Lower requirements. Improvements in pumping mechanism	Power budget allows for greater than 3 months operation using a single 12 V battery
Cost	Estimate between €5,000 and €10,000 initial purchase + running costs (validation, servicing, reagents, waste, etc.)	Fabrication cost is approx. €2,500 per unit, which makes a purchase cost of less than €10,000 feasible
Size	Reduction in overall current size	A compact, self-contained unit has been developed
Measurement frequency	Initially one measurement/day	Frequency of one measurement/30 min can be implemented
Portability	Desirable	System is easily portable by hand
Ruggedisation	Achieved	Sensor system is contained within a break-proof, water- and airtight enclosure

Figure 5.2. National Centre for Sensor Research dissolved oxygen sensor head.

environment. The DO sensor consists of two main parts:

1. An optical probe that houses all of the optical and opto-electronic components, and

2. An IP68 enclosure that houses the sensor's electronic circuitry.

The probe and the electronics enclosure are connected using a 1-m length of IP68-rated conduit, which accommodates all of the necessary connecting cables. Communication to and from the sensor is achieved *via* an RS232 port. The RS232 and power cables are connected to the system through a 3-m length of the aforementioned conduit. The sensor membrane and opto-electronic components are housed in a rugged waterproof probe (see Fig. 5.2), which incorporates a novel optical configuration (see Fig. 5.3) that results in enhanced signal capture and discrimination of background fluorescence, when compared with conventional fluorescence-based sensors.

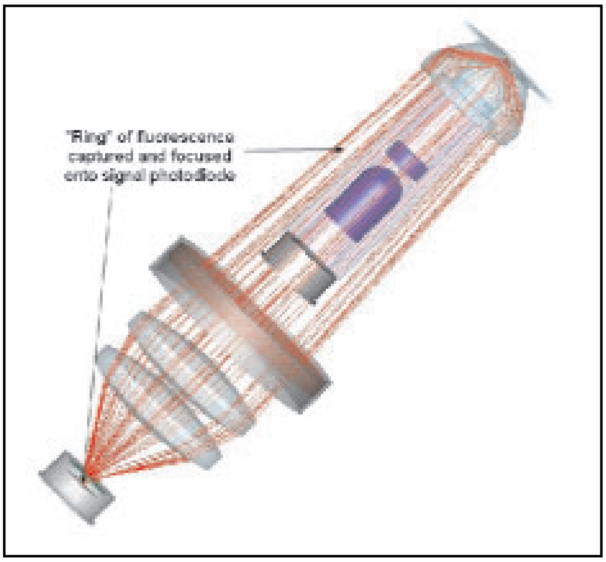

Figure 5.3. Optical configuration of the National Centre for Sensor Research dissolved oxygen sensor.

Over the course of this project, existing optical oxygen sensor technology was adapted and improved upon significantly to produce a sensor that has been tailored specifically to the needs of the SmartCoast Project. The agreed sensor design criteria for the NCSR-developed DO sensor are shown in Table 5.2. The table outlines the objectives that were identified for the DO sensor developed during this project, and also shows how each of the specified objectives has been achieved. The table also shows that the objectives for power consumption, cost, size, measurement frequency, portability and ruggedisation have been achieved or exceeded.

Table 5.2. Summary of dissolved oxygen (DO) sensor design criteria.

Item	Objective	Current status
Sensitivity	1 mg/l DO	1.6 µg/l
Power consumption	Low power consumption	The system has been designed for use in intermittent mode in order to minimise power consumption
Cost	Low-cost device	Each prototype DO sensor cost approx. €2,000; however, this would be reduced substantially in the event of high volume production
Size	Reduction in overall current size, portable	A compact, self-contained unit has been developed
Measurement frequency	Every 1 min	Frequency of one measurement/30 s can be implemented
Portability	Desirable	System is easily portable by hand
Ruggedisation	Achieved	Probe-based sensor is fully waterproof and ruggedised

6 Demonstration of the SmartCoast Technology

The demonstration of the real-time water quality monitoring network in the River Lee in May 2008 allowed the SmartCoast Project team to showcase the integration of a group of water quality sensors into a distributed communication network through interfacing them with the plug-and-play system with ZigBee® telemetry capable of transmitting the data to the SmartCoast server, which processes the data from transmission to the web.

The SmartCoast demonstration looked at monitoring typical water quality parameters by deploying sensors, which:

- Measured water quality parameters
- Collected and managed data
- Communicated the results, and
- Activated responses.

The demonstration trials involved a number of phases, namely testing of the communications, sensors, maintenance requirements, network capability and web page. To achieve this, elements of the technologies were tested well in advance of the final demonstration trial of May 2008. The latter provided the opportunity to test the sensor network as a whole. Five sites were selected for deployment of the sensor systems. The sites on the River Lee extended from the Inniscarra Reservoir to the Tivoli Docks in Cork City. The five sites are shown in Fig. 6.1, and are:

- Inniscarra Reservoir (×2)
- Lee Road
- Lee Maltings
- Tivoli Docks.

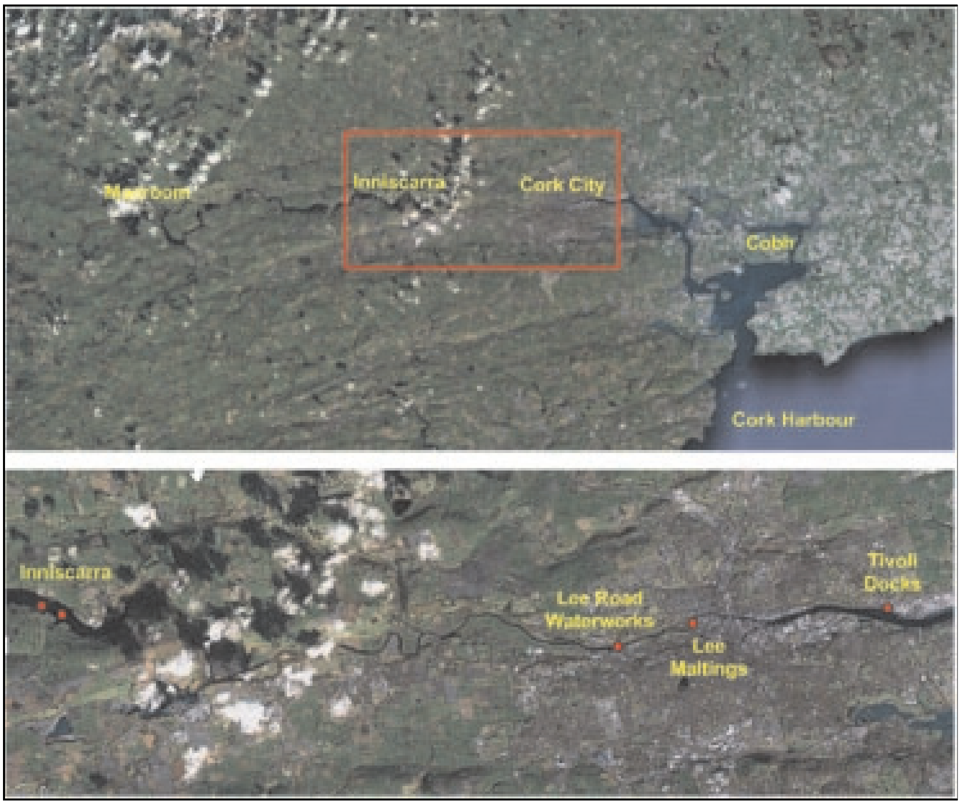

Figure 6.1. Geo-physical presentation of the SmartCoast River Lee deployment.

6.1 Data Collected from the Demonstration

Data were collected from all stations over the course of the demonstration; a representative section of some of the data collected from the stations at Inniscarra and the Lee Maltings are presented in this report.

6.1.1 *Inniscarra deployment*

The deployment at Inniscarra comprised a data buoy, a pumphouse monitoring system and a web access node, operating as a sensor network (see Fig. 6.2). This deployment scenario allowed the demonstrator the capability to demonstrate:

- Routine sampling
- Wireless networking and heterogeneous networking, and
- Plug-and-play interfacing of sensors.

6.1.1.1 Inniscarra data buoy station

Three temperature sensors for water depth profiling were mounted on a Marine Informatics inshore buoy complete with a solar panel and power pack. The sensors were placed at various depths, one directly under the buoy, one at 5 m and one at a depth of 13 m. The data were sampled every 5 min and transmitted to the shore-based access node, for transmission to the web server, using the ZigBee® protocol, to a base station in the pumphouse.

6.1.1.2 Pumphouse multi-sensor station

The pumphouse monitoring station was located in the intake tower for the Inniscarra Waterworks Plant on the Inniscarra Reservoir. The instruments were mounted in a constant flow tank (see Fig. 6.3) in the water tower at the

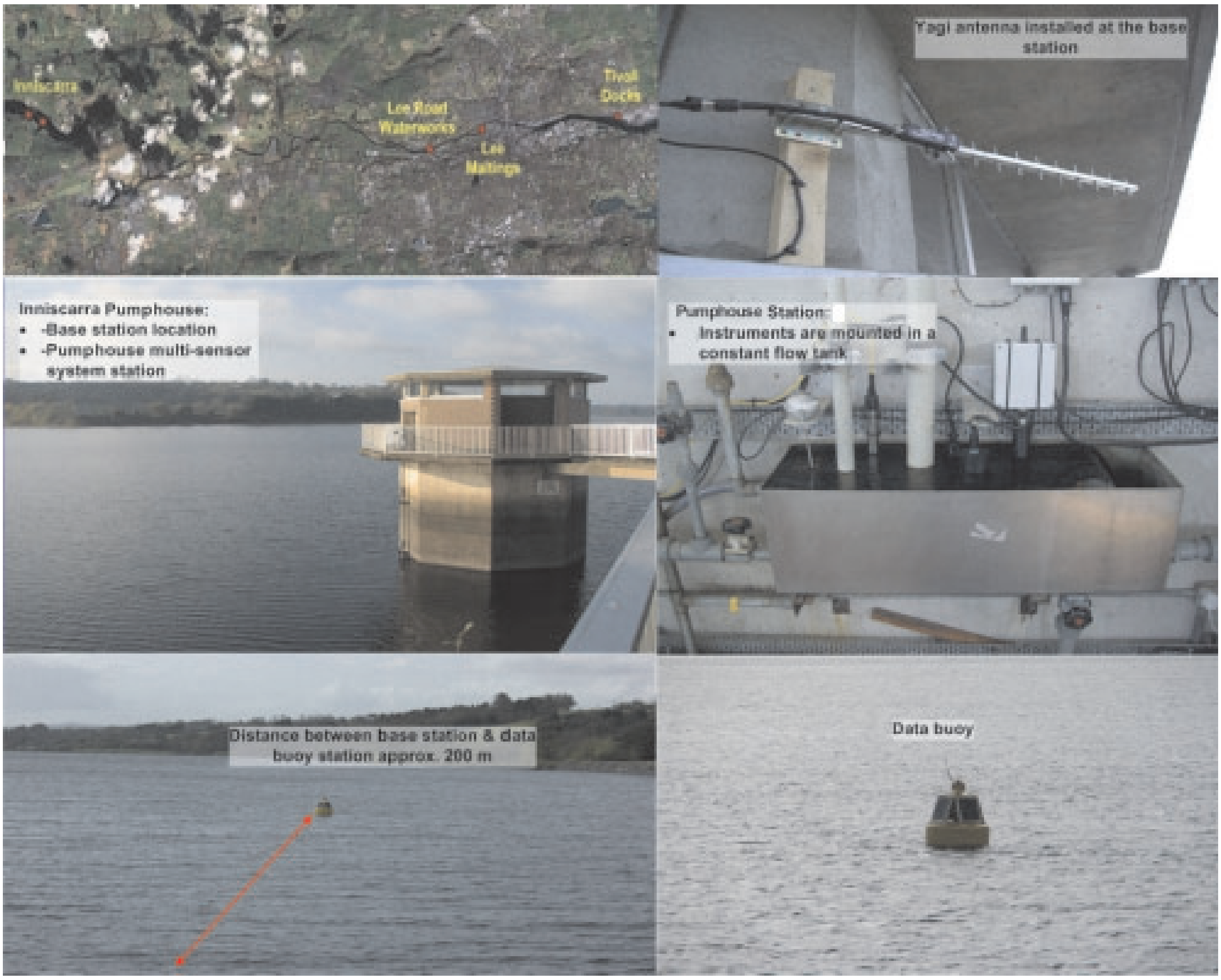

Figure 6.2. SmartCoast deployment scenario for the multi-sensor system at the Inniscarra Reservoir.

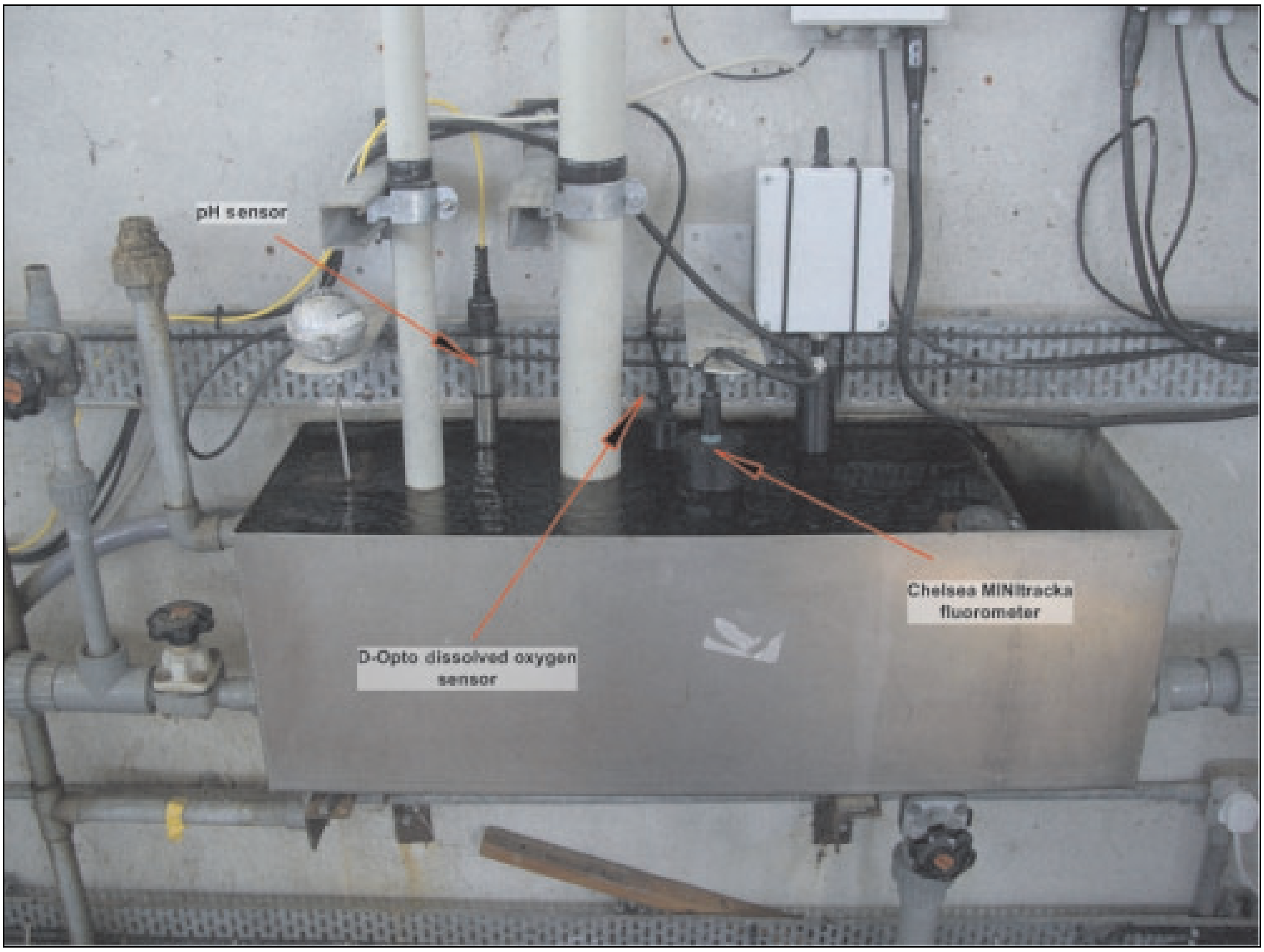

Figure 6.3. The pumphouse monitoring station.

reservoir where water is continually pumped from a depth of approximately 5 m. This station is a Tyndall PSoC plug-and-play system with ZigBee® telemetry. The instruments chosen for this station were a D-Opto DO sensor, a Chelsea MINItracka II fluorometer and a water pH meter.

6.1.2 Deployment of multi-sensor system at the Lee Maltings

The deployment at the Tyndall National Institute at the Lee Maltings consisted of a quay-mounted Tyndall PSoC system with five water/environmental quality sensors that faced directly onto the River Lee, as shown in Fig. 6.4. The deployment site is tidally influenced and, in order to ensure that the sensors remained afloat, sensors were tied between an anchor and a buoy. However, the water-level sensor was attached to an anchor and, therefore, was always at the same position near the river bed. Data were sampled every 15 min and automatically written to the Tyndall website and also to the SmartCoast web server and the Tyndall project page using 802.11 telemetry.

As part of the demonstration, the objectives for this site were to:

- Demonstrate the effects of a long-term deployment
- Implement an automated interface between the wireless ZigBee® with a wide area network over TCP/IP, and
- Evaluate and test plug-and-play interfaces for a variety of sensors for water quality monitoring.

6.1.3 Inniscarra pumphouse, data buoy and Lee Maltings data

The SmartCoast multi-sensor system was installed in the pumphouse at Inniscarra in April 2008 prior to the

Figure 6.4. Location of the multi-sensor deployment in the River Lee.

demonstration in May 2008. During testing it was discovered that there were some problems with readings associated with the Zebra-Tech D-Opto sensor. The DO concentration was fluctuating continuously, with a peak-to-peak magnitude of approximately 2 mg/l, while the temperature readings remained stable. The source of this problem was associated noise in the pumphouse and was successfully resolved by placing a grounding wire from the instrument power ground to a more suitable ground, located just below the multi-sensor system platform. After this solution was implemented in May 2008, the DO concentrations became more stable (see Fig. 6.5). The difference in temperature, before and after the rework, as shown in Fig. 6.5, was owing to the fact that the sensor was placed in a container of water during testing.

The three temperature sensors, located at different depths in order to examine the change in temperature with depth and battery monitoring, were placed at the data buoy station. Figure 6.6 shows the change in

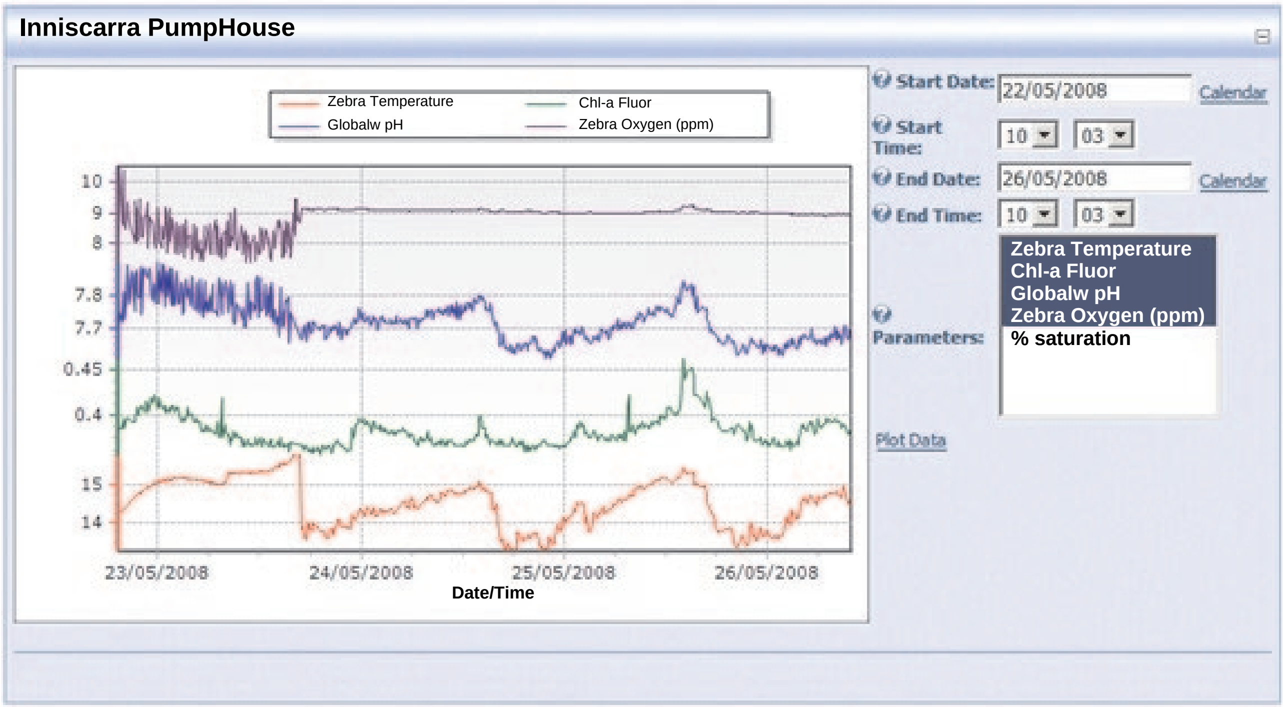

Figure 6.5. Pumphouse readings after May 2008.

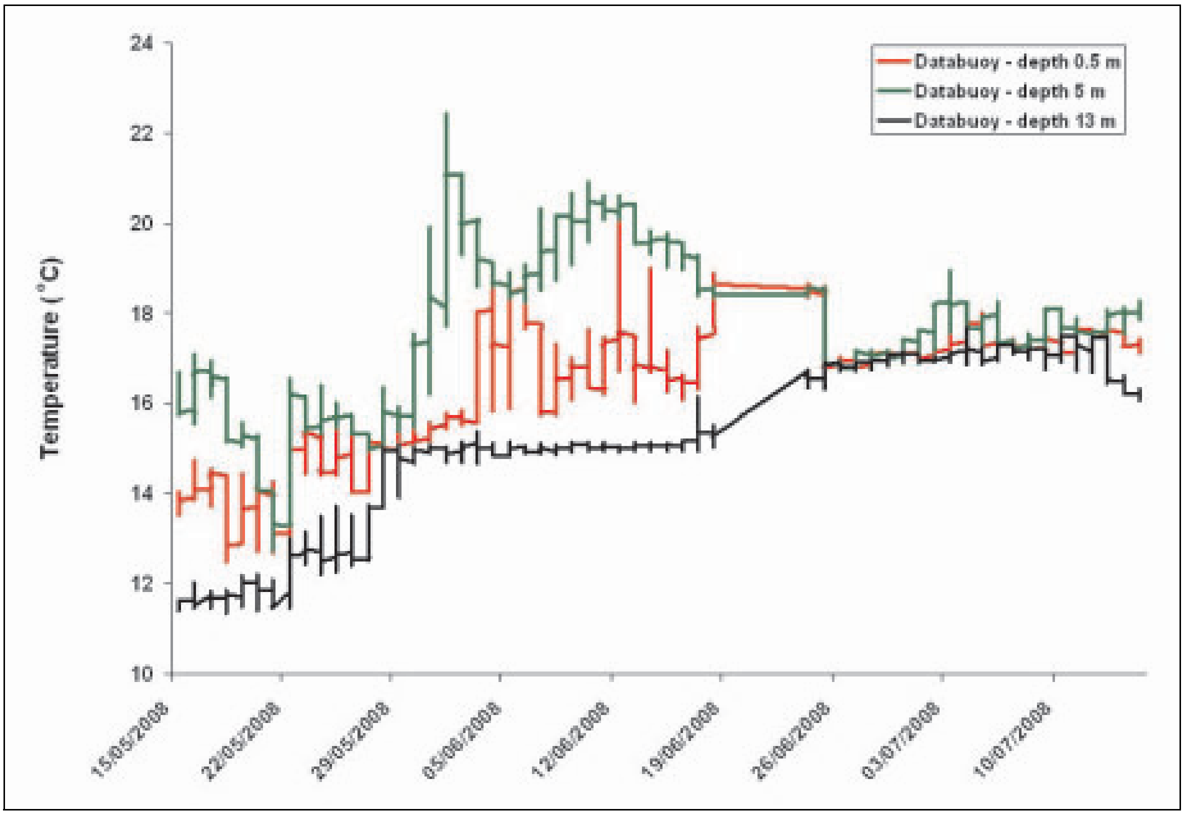

Figure 6.6. Temperature readings from three depths in the Inniscarra Reservoir over time.

temperature over time at the three different depths over the course of the demonstration.

During testing of the sensors, it was found that the temperature sensor, placed at the 5-m depth, was malfunctioning and, as a result, the temperature readings from this sensor were disregarded. As observed in Fig. 6.7, of the two temperature water depth profiles over time, the temperature readings at 13 m were, as expected, colder than the temperature at 0.5 m.

Figure 6.8 displays the temperature measured at the pumphouse and at the buoy station at a depth of 0.5 m. The temperature measured at the pumphouse in general follows the same pattern as the temperature at the 0.5-m depth at the buoy station, with three main differences:

1. The temperature at 0.5-m depth at the buoy station is generally higher than it is at the pumphouse station
2. The temperature changes at the buoy (0.5-m depth) are larger, and
3. When the temperature reaches its maximum at the buoy, it remains there for a longer period of time than it does at the pumphouse station and, when it decreases, it does so more gradually than at the pumphouse.

These results are expected when one takes into account that at the pumphouse the sensors are mounted in a constant flow tank with water pumped from a depth of approximately 5 m.

We can also compare the temperature of the water taken at Inniscarra, at both the pumphouse and the buoy (0.5-m depth), with that of the Lee Maltings site, further down the river. The Lee Maltings site is tidally influenced and the large changes in water temperature, shown in Fig. 6.9, are a consequence of the inward tidal movement of the cooler sea water and the influence of the warmer river water, which flows outwards towards the sea. The aim of obtaining the water depth profile as a function of the temperature

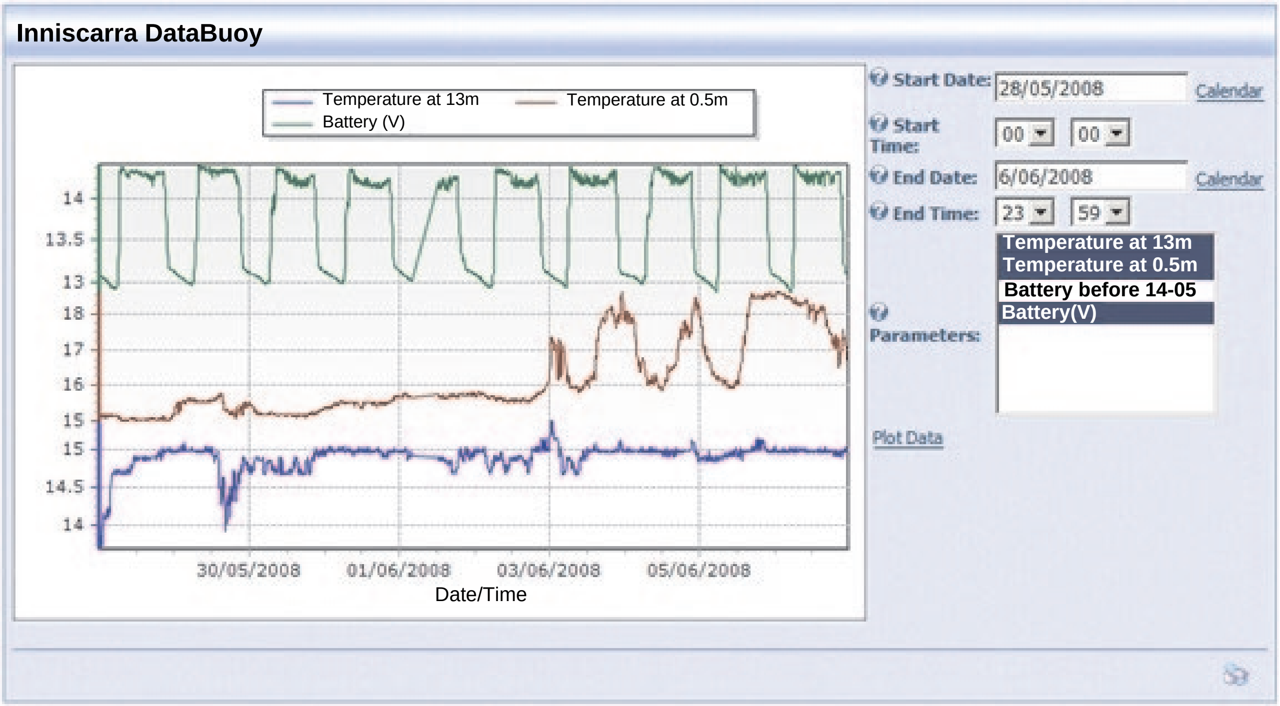

Figure 6.7. Buoy station pumphouse results.

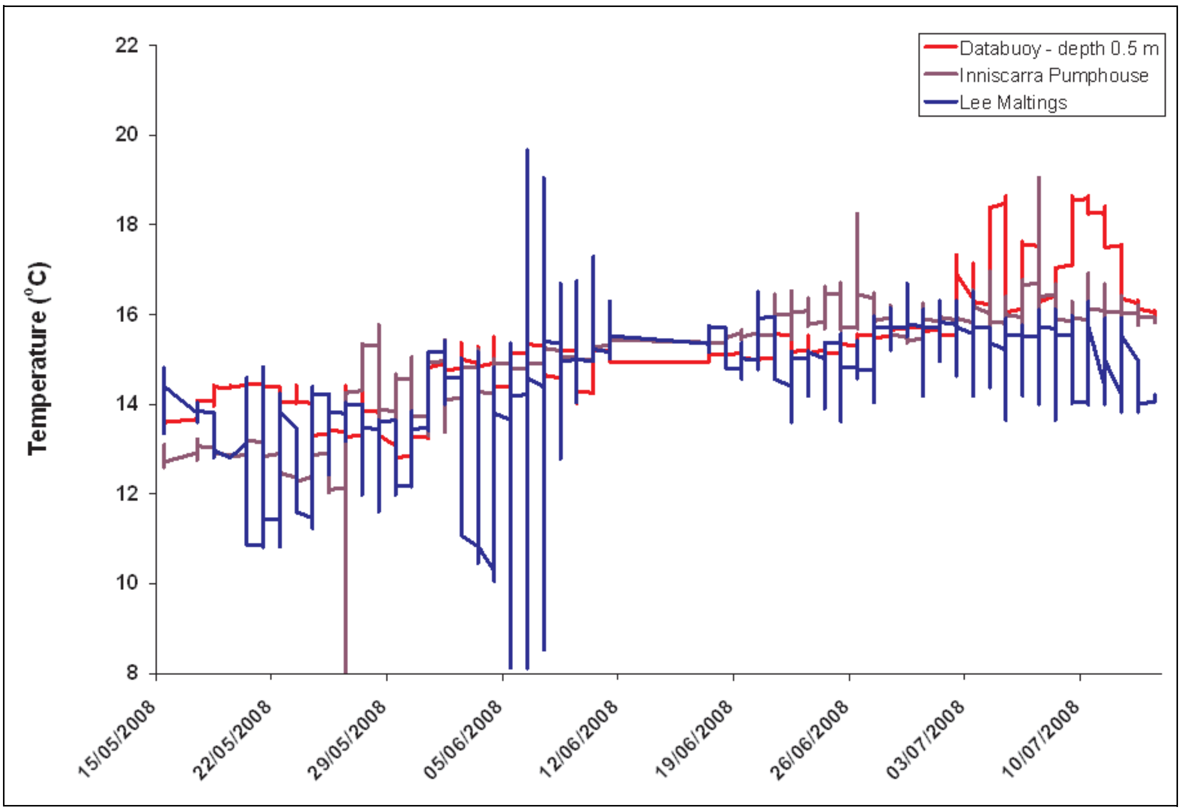

Figure 6.8. Buoy and pumphouse station temperature comparison.

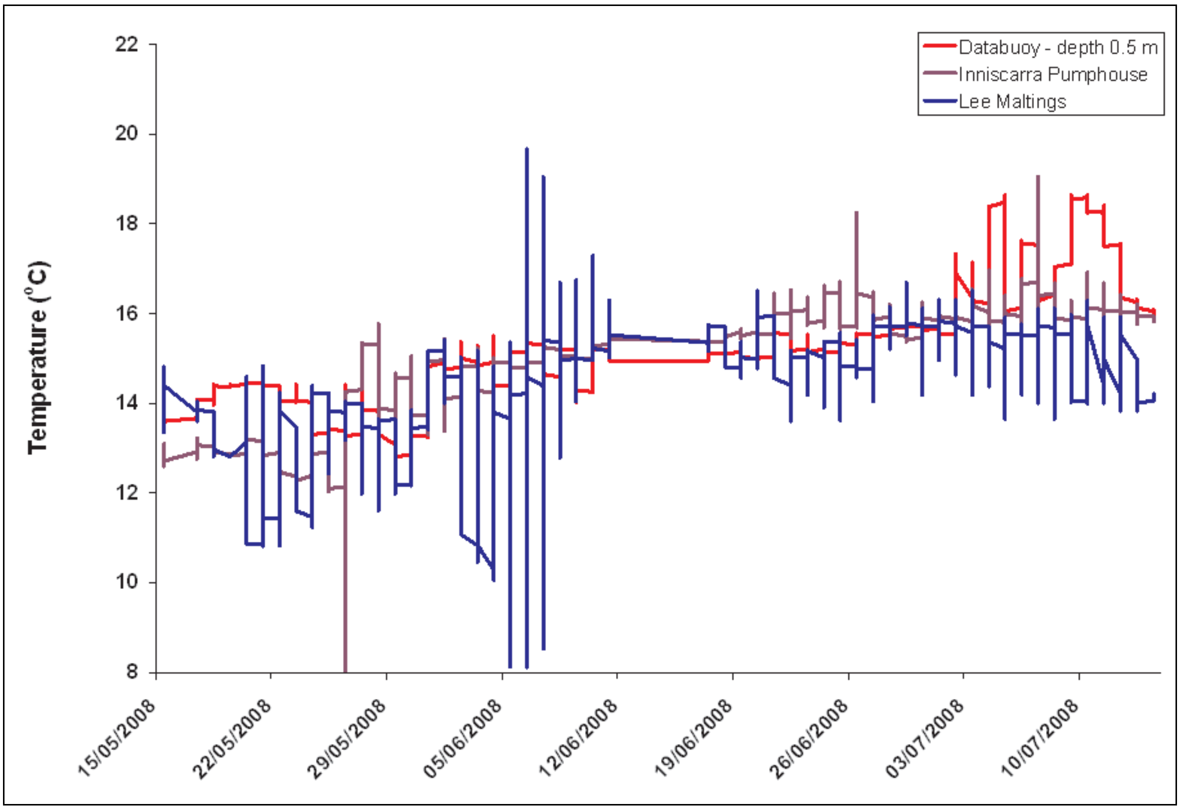

Figure 6.9. Comparison of water temperature readings from three sites (data buoy, Inniscarra (red line), Inniscarra pumphouse (purple line) and Lee Maltings (blue line)) on the River Lee.

and demonstrating the value of the developed wireless sensor network (WSN) was achieved.

Figure 6.10 displays a summary of the readings observed over the course of the demonstration, collected from the pumphouse at Inniscarra. In addition to DO (ppm) (red line) and temperature (blue line), as discussed above, levels of pH (black line) and absorbance at 470 nm (pink line) were recorded. The pH remained stable throughout the period of the demonstration, ranging from 7.2 to 8.4, within the expected range for freshwater bodies.

Figure 6.11 displays a summary of the results obtained from the SmartCoast station at the Lee Maltings site over the course of the demonstration period (May–July 2008). The trends observed in water level (ft) (purple line) and temperature (blue line) reflect the tidal changes and temporal variations of the site. Turbidity (NTU) readings (green line) remained stable throughout the demonstration, indicating the possibility that there may have been a fault with the sensor. The sensor site location and the influence of the tidal change would be expected to cause temporal and spatial changes in turbidity readings and this was not seen in the real-time data collected.

From the short demonstration carried out in the River Lee, the experiences gained can be brought to future developments; in particular, experience on the general handling of devices, platforms and data was of real value, including:

- Sensor maintenance requirements
- Sensor data quality from off-the-shelf devices
- Access issues for sensor maintenance
- Data collection and handling issues and development of web access, and
- Issues in relation to permissions.

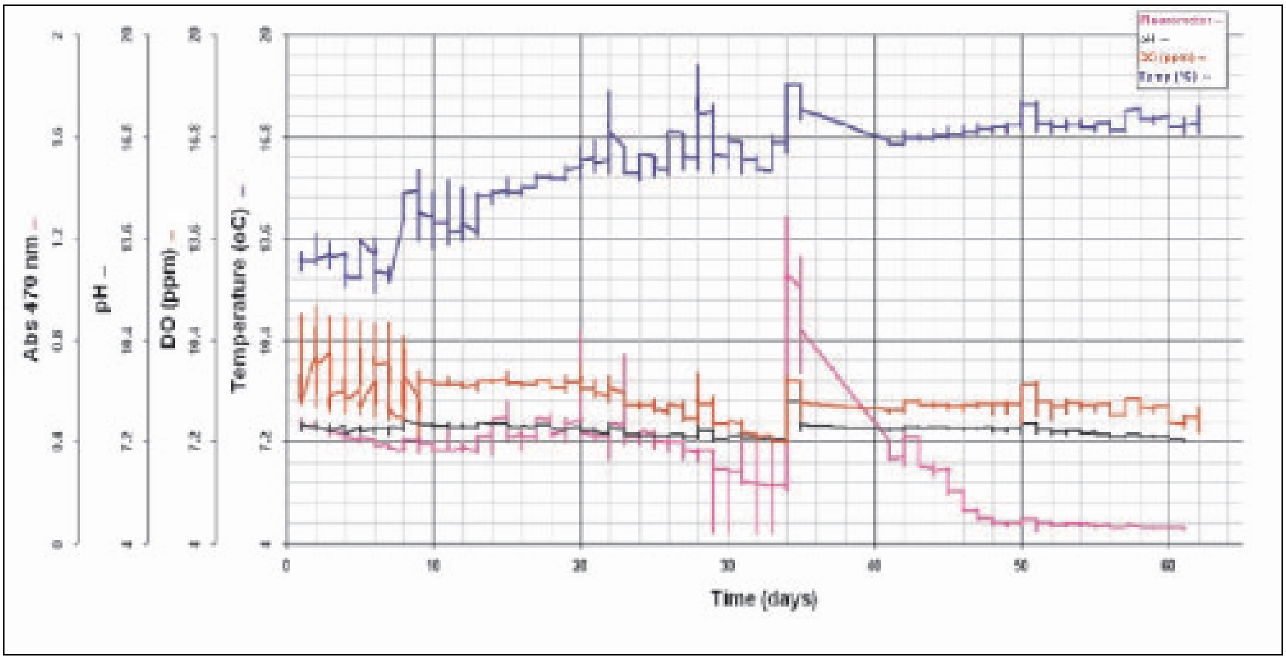

Figure 6.10. Pumphouse sensor readings over the course of the demonstration: fluorimeter (pink), pH (black), DO (red), and temperature (blue).

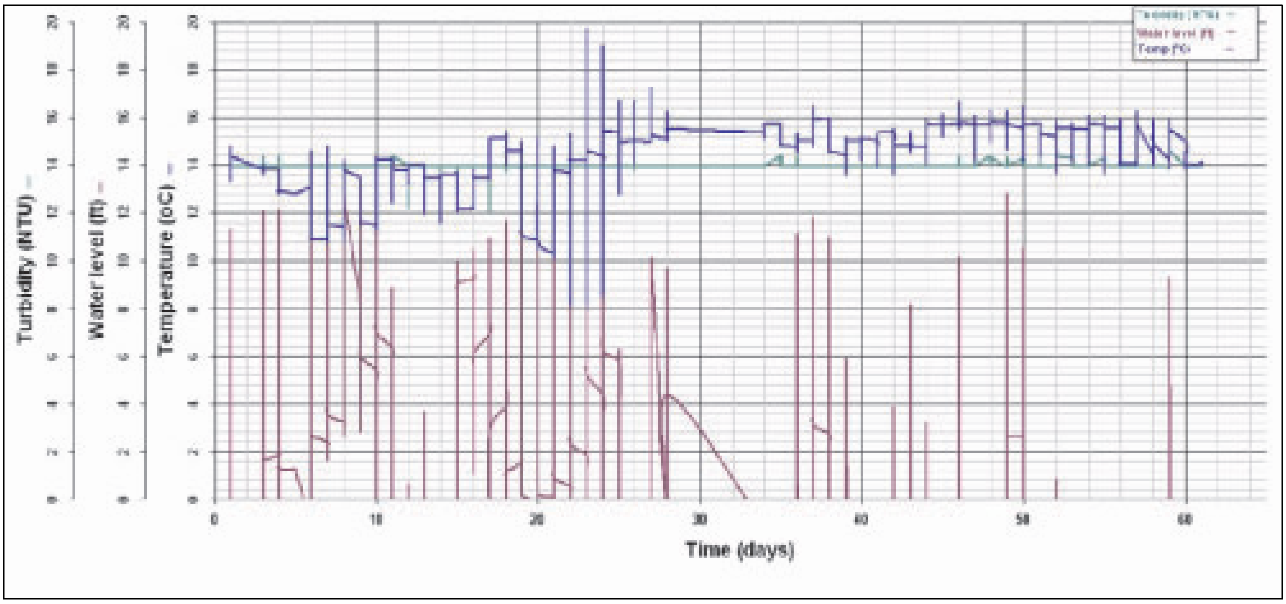

Figure 6.11. Lee Maltings sensor readings over the course of the demonstration: turbidity (green), water level (purple), and temperature (blue).

7 Lessons Learned from the SmartCoast Project

7.1 The Requirement for Monitoring

Historically, investment in monitoring of European waterbodies has been low, partly owing to the high costs associated with sample collection and subsequent analyses in the laboratory. The monitoring at river basin level for the WFD is a significant financial burden using conventional sampling where most researchers rely upon manual sampling or expensive automated samplers, both of which limit spatial and temporal resolution of data, and laboratory-based techniques. The use of relatively inexpensive *in-situ* sensors offers the potential to considerably reduce these costs, making it possible to monitor an increasingly wider set of parameters in the field, as well as providing more useful, continuous monitoring capabilities to give an accurate idea of changing environmental and water quality.

7.2 The Ideal System

The ideal monitoring system of the near future might consist of a network of sensors, deployed at key locations, capable of autonomous operation in the field for perhaps a year or more. Currently, the building blocks necessary to achieve the ideal scenario of the real-time simultaneous measurement of multiple water quality parameters are available. However, the quality of some of the more sophisticated sensors for nutrients needs to be improved, while using the simpler devices in clever ways in embedded networks.

7.3 Wireless Sensor Systems

The SmartCoast Project has highlighted the potential of wireless sensor systems, enabling the scientist to observe and monitor environmental variables of interest. Data from monitoring stations can be analysed and communicated by wireless technology for statistical processing and interpretation by expert systems in the office. Rising trends for any constituent of interest or breaches of Environmental Quality Standards (EQSs) will alert relevant personnel, as an alarm sent to their mobile phone or by e-mail, or lead to other appropriate responses. These personnel can then intercept serious pollution incidents by evaluating the change in water quality parameters measured numerous times every day. The capability of the developed SmartCoast multi-sensor system to continuously sample and communicate up-to-date information will enable overall monitoring costs to be reduced, while providing better coverage of long-term trends and fluctuations of parameters of interest. It is envisaged that the deployment of sensor systems similar to SmartCoast will allow a new approach to study the environment and new field methods to be conceptualised, and will provide new solutions to scientific problems.

7.4 New Technologies of the SmartCoast Project

7.4.1 Water quality monitoring platform

A multi-sensor water quality monitoring platform has been developed in the project. This incorporates novel sensor interface technologies that can be reconfigured to meet the monitoring requirements of a given scenario using a wide variety of sensor input types. The sensor interface capabilities enabled by the developed wireless sensor network platform allow for integration of a wide variety of commercially available sensors.

7.4.2 Novel sensor technology

Two sensors capable of measuring phosphate and dissolved oxygen were developed by the consortium during the project. The phosphate sensor is suitable for long-term monitoring of phosphate levels in natural waters. The system incorporates sampling, pumping, reagent and waste storage, colorimetric detection and wireless communication into a compact and portable device. Currently, the system has a linear dynamic range between 0 and 20 mg/l and a limit of detection of 0.3 mg/l.

Dissolved oxygen sensor technology was developed, providing a sensor probe that is fully waterproofed and ruggedised, incorporating a novel optical configuration, and is capable of intermittent operation, facilitating its use in battery-powered systems. The sensor is fully temperature compensated and utilises threedimensional calibration equations, which maximise accuracy. These two novel devices were tested in the demonstration phase and while the phosphate system performed well, the DO system is in need of further work to enable long-term deployment in the aquatic environment.

7.4.3 Biofouling research

In the SmartCoast project some fundamental research into the area of biofouling was carried out. The antifouling research carried out at the NCSR involved the following:

- Establishment of the nature of the biofouling process
- Development of mechanisms to test the degree of biofouling
- Design and development of novel materials that can be used on optical sensors and sensor platforms to reduce the effect of biofouling
- Testing of novel materials in the laboratory and in the field, and
- Applications of materials to sensors.

It was found that preventing the initial bacterial attachment to surfaces would greatly reduce the impact of biofouling on surfaces. Thus efforts in this study were focused on preventing bacterial adhesion by using anti-microbial agents in the material design. Materials included long-chain plasticisers, surfactants, nanoparticles and natural products, all of which showed promise in microbial tests but fouling still took place when materials were exposed to the environmental waters. Where copper coatings were used fouling was greatly reduced.

Further to the success of the research carried out in SmartCoast into biofouling, this research on materials has continued within the NCSR.

7.5 Scale-Up of Sensors

The Marine Institute awarded additional resources to the SmartCoast project to enable the scale-up of sensors and platforms developed in the project. Several issues were highlighted during the design, construction and testing of the sensors. The fabrication of multiple units of the sophisticated sensors was a significant challenge to undertake and issues arose associated with moving from a laboratory-based prototype sensor to a ruggedised system that could be used in the field. Some of the key points to be taken from the experience of the task include:

- A generous time frame is required in order to realistically make allowance for delays in sourcing and delivery of components, as well as for the very significant time/manpower requirements involved in fabricating and validating multiple units of a system.
- In so far as possible, the design of the system should be finalised prior to undertaking such a scale-up task to avoid potential conflicts between development and fabrication processes.
- The approach taken should be that used in this project, where funding was provided, and must allow personnel with the appropriate skills to work full-time on the fabrication process.

7.6 Recommendations for the Future

In order to achieve the challenging objective of realising the ideal monitoring system of the future, researchers need support at a variety of levels:

- Reference testing sites (Smart Sites) should be developed for novel technologies and continuous validation that could be used by researchers, companies and agencies, as well as standardisation organisations, to test and validate, and possibly standardise, technologies. These Smart Sites could act as reference test locations for agencies, academic researchers, and technology development companies to test their technologies.
- Resources are needed to develop prototype devices and laboratory/environmental trials; this should then be followed by scale-up of the devices for full-scale field trials and validation.
- Not only is there a need for these devices but they must be robust, reliable and capable of use over long periods of time, without loss of response and need for calibration. The latter is a huge challenge

and thus needs further development and validation.

- There is a real need for the funding agencies to establish collaborative research efforts in areas of sensor development, communications technologies, data management and user group interface. The need for interpretation of sensor-based data, compared with spot sampling, is great, and while some studies have been undertaken to investigate this, it can only be done effectively when sensors are tested in the field over long periods of time.

7.7 Summary of the Success and Challenges of the SmartCoast Project

While there were many successful stages in the research, some difficulties arose. These include the lack of suitable long-range communication at the time, the issue of sensor fouling (which is a continuing problem for sensor use in certain areas) and the challenge of scaling up the novel sensor systems. While an objective of the research was to establish cost-effective solutions for monitoring, the technology developed did not meet that requirement. Further development of the sensors, platforms, networking and power capability is required to achieve this challenging objective.

In relation to the project tasks, a number of key successes may be identified:

1. Novel sensors for phosphate and dissolved oxygen were developed and tested
2. Sensors were integrated successfully into a network for continuous monitoring
3. Data collection was enabled in real time and near real time
4. The network was field tested and validated and recommendations for the future were established
5. A smart water platform was developed and tested, and
6. A strong alliance with users was established and valuable information for development of monitoring technology was gained.

To summarise, a valuable consortium of researchers, industry and agencies has been established and will enable future developments with greater ease and uniform thinking. Secondly, novel sensors and component technologies have been developed, some of which will be used in future work (Section 7.8), and companies involved have gained from the research expertise and access to new technologies for market which they may exploit. Most significant is the knowledge and expertise gained in the area of monitoring technology which can be used in the future.

7.8 The Next Stage of Demonstration

Further to the success of the SmartCoast project, some of the consortium have established a longer-term deployment of sensor technology in the River Lee, Co. Cork, from early 2009. Taking significant experience gained from the SmartCoast project (sensor selection, maintenance and validation of sensors, sensor deployment options, communications options, power, etc.) and the PSoC technologies developed, an integrated network of sensors is being deployed for 12 months. The data will be collected in real time and ultimately will be placed on the website (to be developed in the project) for access. The project team is focused on demonstrating the deployment continuously over a longer term (12 months). Working closely with future users, the project team aims to:

- Establish protocols for successful monitoring of water quality
- Build confidence in potential users of monitoring technology, and
- Encourage users to drive demonstrations in the future to meet their own particular needs.

The successful deployment of monitoring technology in the River Lee following the SmartCoast project highlights the value gained from the R&D carried out over the 3-year period. This deployment does not encompass all sensor platforms, but is a small step in the right direction.

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