A Smart City-Smart Bay Project - Establishing an Integrated Water Monitoring System for Decision Support in Dublin Bay

Fiona Regan, Timothy Sullivan, Ciprian Briciu,
Helen Cooney, Kevin Murphy
Marine and Environmental Sensing Technology Hub (MESTECH)
National Centre for Sensor Research
Dublin City University
Dublin, Ireland
Email: Fiona.regan@dcu.ie

Dian Zhang, Edel O'Connor,
Noel O'Connor, Alan Smeaton
CLARITY Centre for Sensor Web Technologies
Dublin City University
Dublin, Ireland

***Abstract*—Environmental and water quality monitoring is key to measuring and understanding the chemical and biological quality of water and for taking reactive remedial action. Over the coming years, monitoring of water bodies 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. However, the traditional spot/grab sampling using conventional sampling and laboratory based techniques can introduce a significant financial burden, and is unlikely to provide a reasonable estimate of the true maximum and/or mean concentration for a particular physico-chemical variable in a water body with marked temporal variability. When persistent fluctuations occur, it is likely only to be detected through continuous measurements, which have the capability of detecting sporadic peaks of concentration. The aim of this work is to demonstrate the potential for continuous monitoring data in decision support as part of a smart city project. The multi-modal data system shows potential for low-cost sensing in complex aquatic environments around the city. Continuous monitoring data from both visual and water quality sensors is collected and data from grab samples collected support the observations of trends in water quality**

Keywords - Continuous water monitoring, estuary, marine, decision support, turbidity, salinity.

I. Introduction

The use of *in-situ* sensors capable of continuously sampling chemical and physical parameters offers the potential to reduce costs, provide more up-to-date information and a better representation of long-term trends in the fluctuations of pollutant concentrations [1] in aquatic environments. 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 [2] [3]. 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 life-time 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 a challenge. The area of wireless sensing, and particularly, the concept of wireless networked sensors, is fast becoming one of the most dynamic and important areas of multi-disciplinary research [4] [5].

A. The requirement for monitoring

Historically, investment in the monitoring of European water bodies has been low, partly owing to the high costs associated with sample collection, and subsequent analyses in the laboratory. However, monitoring of water, globally and within Europe, will increase over the coming years, in response to the needs of the Water Framework Directive and the pressures of climate change, which will lead to resource scarcity and water quality changes. The use of relatively inexpensive *in-situ* sensors offers the potential to reduce costs considerably, 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. As mentioned previously, the accurate measurement and detection of environmental pollutants is feasible under laboratory-controlled conditions but doing so with continuous *in-situ* monitors remains the most challenging aspect of environmental sensing. One of the advantages of wireless sensor networks is that they enable remote continuous monitoring of the environment. Data from monitoring systems can now be used for a variety of applications in addition to protection of the environment [6] [7] [8].

B. The ideal system

Although it is evident that some elements of this ideal monitoring system are in place, ongoing research and development is required in several areas relating to both sensor technology and field-testing.

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 measurement of multiple water quality parameters, simultaneously, in real-time are available [9]. However, as a scientific community, we need to improve the quality of some of the more sophisticated sensors for nutrients, while using the simpler devices in cleverer ways in embedded networks to make this ideal truly achievable. Data from monitoring stations can be analysed and communicated by wireless technology, for statistical processing and interpretation by expert systems, from the office. Alerts can be issued to relevant personnel - through an alarm sent to their smart phone or by e-mail - when worrying trends for any constituent of interest or breaches of Environmental Quality Standards (EQS) are detected through the evaluation of water quality parameters measured numerous times per day. These personnel can then intercept serious pollution incidents or lead the response they deem appropriate.

The aim of this work is to outline the potential for continuous water quality monitoring in decision support as part of a Smart Bay element [10] [11] to a broader connected city project in Dublin. Over the coming years, this SmartBay project will see the expansion of a multi-modal sensor and data network in Dublin bay for monitoring water quality and flooding in particular. The latter will consist of a number of sensor deployments, including visual sensing systems, modelling and additional available data sources. The data collected over the course of the SmartBay project can be utilized for other applications depending on user requirements or emerging applications, with particular emphasis on water in the city, port and coastal area.

In this paper data from two sites in Dublin Bay will be discussed in terms of event detection and decision support opportunities. The multi-modal data system shows potential for low-cost sensing in complex aquatic environments such as estuaries. Continuous monitoring data from water quality sensors is evaluated and analysed along with data from grab samples, with the latter supporting the observations of trends from the water quality monitoring systems. The scenarios provided are a snapshot of the potential value of such a monitoring system in building a SmartBay infrastructure.

This paper introduces continuous monitoring of environmental water parameters using *in-situ* sensors in the context of a Smart City-Smart Bay project. In Section II both of the monitoring locations used in the study are outlined. Section III describes the technology employed at the sites, how it is used and maintained as well as the methods employed to gather and analyse the environmental samples. The results obtained from the work are presented and discussed in Section IV. Finally the conclusions garnered from this research are detailed.

II. MONITORING LOCATIONS

A sensor sonde was located at two sites in Dublin Bay (Fig. 1); Malahide Estuary (lat: 53° 27′ 14″, long:−6° 9′) and Poolbeg marina (lat: 53° 20′ 39”, long:−6° 13′). Visual sensing technology was also deployed at Poolbeg to track vessel movement in the port area. A sampling regime informed by the continuous sensor systems was instituted to collect grab samples. The two estuaries were selected for this study as they represent the variety of activities in Dublin Bay, with a wide array of stressors and user groups.

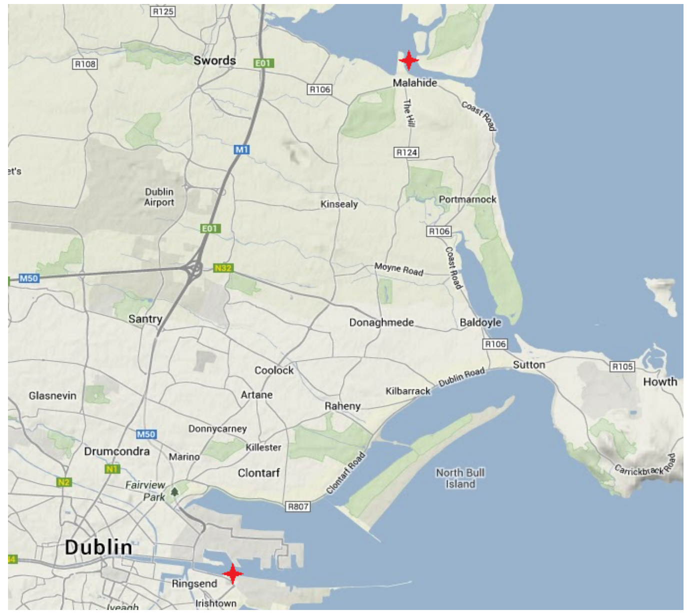


Fig. 1: Map of Dublin Bay area with the location of the working sites indicated by the red marks on the map.

A. Malahide Estuary

As outlined by O'Boyle and Silke [12] the area around the Malahide deployment is a "typical estuarine body characterised by an elongated shallow channel demarcated at one end by a river which is the source of freshwater input and associated nutrients, and at the opposite end by the sea, which is a source of tidal seawater influence". Under the EU Habitats and Birds directives the estuary is both a special area of conservation (SAC) and a special protected area (SPA) and is divided in two by a viaduct built in 1844 [13]. It is a lagoon in character due to a sand spit gradually cutting it off from the sea.

The inner estuary on the left hand side of the bridge is fed with freshwater from the Broadmeadow river and the outer estuary is mainly influenced by the Irish Sea which drains almost completely at low tides. The inner estuary does not drain at low tides apart from the extreme inner estuary. As with all estuaries the average water movement is towards the sea, but the Malahide/Broadmeadow is a mixed estuary [14] as the river flow is less dominant than the tidal flow. The main pressures affecting the estuarine catchment water quality is the presence of waste water treatment plants and sewer overflows.

B. Poolbeg Marina

Poolbeg Marina, on the lower Liffey Estuary, is a busy port environment with a diverse ecosystem that includes benthic communities [15], fish and shellfish, marine bird populations and some marine mammals. The site forms a zone of passage for salmon and sea trout migrating from the sea to spawning areas upriver and for juveniles migrating from the river to the sea. The area hosts much human activity including heavy port use, marine transportation and aquaculture. The topography of the estuary is heavily modified, being walled for its whole length and undergoing regular dredging.

The site is located in the upper part of the estuary, where ship traffic is less intensive and thus easier to monitor. The water depth in the area is approximately 8 m and the width of the channel is approximately 260 m. The area acts as a buffer zone for the freshwater input and the tidal flow. Stratification is present due to denser salt water settling at the bottom with fresh water at the surface and also to seasonal heating which causes a differential event, with warm water in the surface layer isolated from the colder, bottom layer. Overlaid on these natural effects are changes attributed to anthropogenesis including input of pollutants (run-off, storm drains, sewage treatment discharges, industrial discharges, port activity and recreational boating) and the modification of flow (upstream dam releases). All of these changes effect the chemical and physical parameters at the site increasing its complexity.

III. TECHNOLOGY DEPLOYED AT BOTH SITES

As discussed earlier a multi-parameter sonde from YSI Hydrodata UK, equipped to measure turbidity (NTU), optical dissolved oxygen (mgL^{-1}), temperature (°C), conductivity (mS/cm) and depth (m), along with a telemetry system (EcoNet), was purchased and deployed. The sonde was placed at a depth of 2.5 m and data was collected with a sampling interval of 15 min. The power supply was a 12 VDC external battery and the data was recorded to an internal logger. The data was also transmitted via GPRS to a web-based server were it can be visualized in real-time or downloaded. Deployment and data collection at Malahide occurred from March until May 2012, with the Poolbeg site on-line from 1$^{\text{st}}$ October 2010 until the present (June 2013).

A. Maintenance Protocols

The operation of the system was checked daily by reviewing the sensor function, the battery levels and telemetry operation. Site visits were carried out for maintenance purposes where cleaning, calibration and validation measurements were performed. A ProPlus hand-held multi-parameter instrument from YSI UK was used to check temperature, dissolved oxygen and salinity and a portable turbidity meter Turb®430 IR from VWR Ireland was employed to validate turbidity measurements. These instruments were laboratory calibrated prior to site visits, which occurred every two weeks for the cold season and weekly during spring. This frequency was generally governed by the biofouling rate of sensors and, occasionally, by a malfunction of the telemetry system. Copper tape and mechanical wipers (for the optical sensors such as DO and turbidity) were used to limit the fouling rate. A protocol for the operation and maintenance of a continuous water quality monitor at sites with rapidly changing conditions was adapted from Wagner et al. [16]. This process is illustrated in Fig.3. On arrival at the site, the following steps were performed:
1) readings were recorded from the sonde and compared to the pre-calibrated meters;
2) if a large different was observed, an insulated bucket was filled with ambient water with both the sonde and the calibrated meter placed inside and allowed to run in parallel while logging data internally;
3) the sonde and the sensors were cleansed and step 2 was repeated;
4) the sonde was removed, rinsed thoroughly and it was checked against the calibration standards and readings were recorded, in the case of the calibration criteria* being breached a re-calibration was performed.

To account of the variable nature of turbidity it's sensors pre-cleaning measurements were made in a bucket of tap water.

$*$ calibration criteria: temperature ± 0.2°C; DO ± 0.3 mgL^{-1}; specific conductance $\pm 3\%$ of the measured value; turbidity $\pm 5\%$ of the measured value.

B. Rainfall Data

Daily rainfall data was collected from the Irish Meteorological Service from all the meteorological stations in Dublin area. Stations (Fig.2) were selected based on the spatial distribution around the monitoring locations and the data obtained from all the stations was averaged to compute a single daily mean.

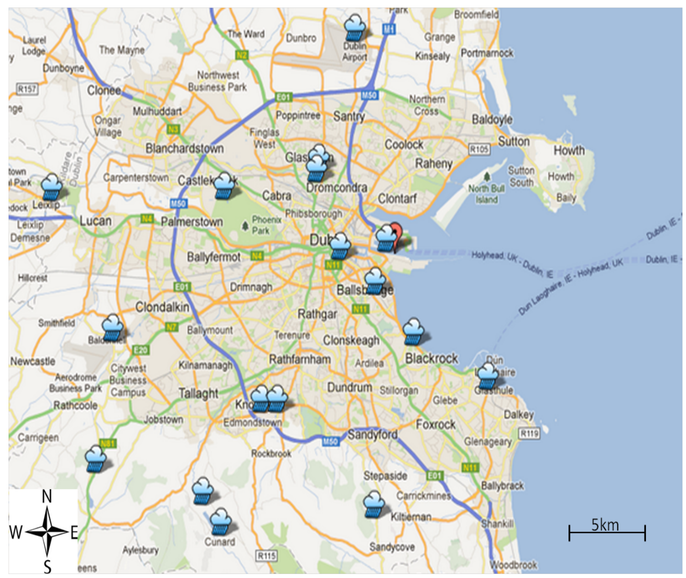


Fig. 2: The location of rainfall data stations around Dublin from which a daily mean was established.

C. Grab Samples

Water samples for phosphorus (P), total suspended solids (TSS) and microbiological analysis were collected in August and September 2012. Samples were collected in the morning, before and after the arrival of the ferry at three depths: 0.5, 2.5 and 4.5 m. All the samples were collected in triplicate using a Wheaton grab sampler, and were transported to the lab under ice.

D. Microbial analysis of water samples at Poolbeg

Water samples were collected in sterile 500 mL high-density polypropylene (HDPP) bottles. Samples were transported to the lab under ice within 2 hrs and inoculated within 4 hrs after collection. A *Colilert-18*®/Quanti-Tray 2000® system (IDEXX Laboratories) was used for the enumeration of Coliforms and *Escherichia coli* and an Enterolert ® /Quanti-Tray 2000® system (IDEXX Laboratories) was used for the enumeration of *Enterococcus* (ENT). The enumeration protocol was followed in accordance with the manufacturers instructions. Aliquots of 10 mL from the original water sample

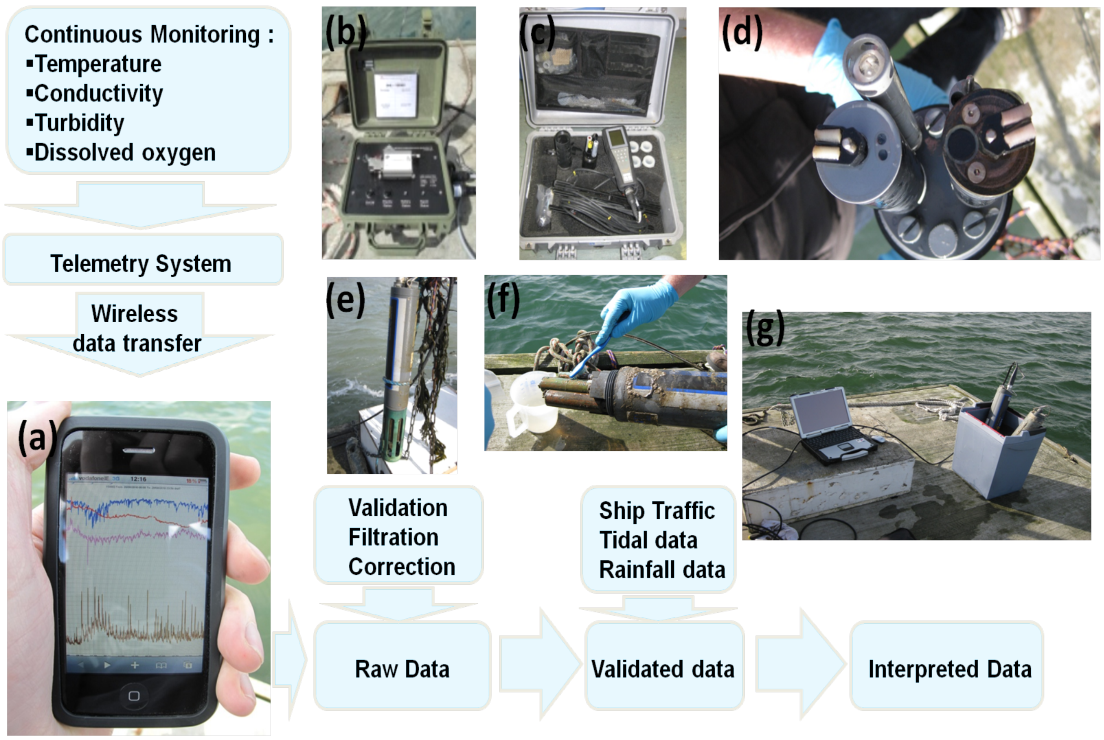


Fig. 3: Data collection, analysis and interpretation; (a) real-time data visualisation in the field using smart phones, (b) telemetry system, (c) YSI Pro-Plus hand-held sensor used for on-site validation, (d, e) YSI 6 series sonde, (f) sensor cleaning and (g) validation procedure.

were diluted 1:10 with sterile de-ionised water into 100 mL bottles. After the addition of Colilert-18 and Enterolert, samples were inoculated into Quanti-Trays and sealed. For *E. coli* and coliform enumeration, samples were incubated at 37.0°C for 18 to 20 hrs. Following incubation the Quanti-Tray wells were read for yellow colour indicating the presence of coliforms and for blue fluorescence indicating the presence of *E. coli*. For ENT enumeration samples were incubated at 41.0°C for 24 to 28 hrs after which blue fluorescent wells were counted as positive. The number of positive wells was recorded for both tests and converted to most probable number (MPN) estimations using tables provided by the manufacturer. For quality control, replicates of positive controls of *E. coli* ATCC 11775 and *Enterococcus faecalis* ATCC 19433, negative controls and laboratory reagent blank were analysed for each sample batch.

E. Phosphorus analysis for Poolbeg samples

For Phosphorus (P) analysis, a protocol based on the phospho molybdenum blue method was adapted from Murphy and Riley [17] and Standard Method 4500 P-E [18] was used, as described below. Samples were collected in 500 mL HDPP bottles and transported to the lab on ice, where 250 mL of each samples was filtered through 0.45 μm cellulose nitrate filter membranes.Soluble reactive phosphorus (SRP) and total soluble phosphorus (TSP) were determined from the filtered samples, while total phosphorus (TP) was determined from the raw water samples. Total particulate phosphorus (TPP) was determined as TP $-$ TSP $=$ TPP. For TSP and TP analysis samples were digested using acidified potassium persulfate and autoclaving for 40 min at 121°C [18]. The method detection limit (MDL) was 11.0 gL^{-1} with a useful analytical range between 36.9 μgL^{-1} and 1 mgL^{-1} PO_4-P using a Shimadzu UV-1800 spectrophotometer.

F. Data management and processing

In situ sensors operating in harsh environments like those experienced at Malahide and Poolbeg are prone to fouling and drift, leading to data compromise. Before the data can be used, it has to undergo a set of quality assurance and quality control procedures to ensure that anomalies and spurious data values are removed. Wagner *et al.* [16] provide guidelines and standard procedures for correcting errors in continuous water quality data streams and Horsburgh *et al.* [19] give examples of raw data containing errors that have to be corrected. In the initial stage of this process, raw data was reviewed daily and anomalous data and out of range data were flagged [19].

Data was fully reviewed after each site visit and corrected if necessary. Out of range values were short-lived (no more than one sensor value) and were corrected manually by interpolating adjacent values. Sensor fouling occurs gradually over time leading to shifts in data after cleaning and re-calibration. Data correction for fouling drift was applied between two servicing dates as described by Wagner *et al.* [16], only when the combined absolute value for calibration and fouling error exceeded the following criteria: temperature ± 0.2°C; DO ± 0.3 mgL^{-1}; specific conductance $\pm 3\%$ of the measured value; turbidity $\pm 5\%$ of the measured value.

Sensor drift is assumed to occur at a constant rate throughout the correction, with fouling commencing as soon as the sonde is deployed in the aquatic environment. Zero correction is applied at the start of the interval, the full correction at the end of it and between these dates data is linearly interpolated.

Eq. 1 [19] was used in this case for linear drift correction,

$$V_c = V + (V_f - V_s)\left(\frac{T_t - T}{T_t}\right) \tag{1}$$

where V_c is the drift corrected value, V is the original measured value, V_f is the response of the sensor immediately before cleaning and validation at the end of the correction interval; V_s is the response of the sensor after cleaning and calibration; T_f is the total time interval for which the correction is applied and T is the time between the end of deployment and the time when the value is measured.

IV. RESULTS

This section provides an overview of results garnered from two estuarine sites in Dublin where continuous monitoring has been carried out over the past three years. Data from sensors and other sources, has shown that events can be identified and this can trigger the need to sample for more specialist analysis. This event driven approach to sampling is a much more reliable approach to water resource management than the current methods. These long term continuous data sets provide the basis for the development of a SmartBay dimension to the Dublin SmartCity project currently underway.

The data collected from the sites provides evidence that:
a) sensor readings (specifically turbidity and DO) can indicate the onset of a primary productivity event (algal bloom);
b) temperature and DO readings can provide an early warning of the latter event;
c) turbidity data can indicate the correct time to sample a water;
d) bacteriological and nutrient analysis can confirm the value of the turbidity readings as a decision support.

The multi-modal data system shows potential for low-cost sensing in complex aquatic environments around the city.

A. Malahide Estuary

Average surface temperatures for near shore coastal waters are influenced by freshwater run-off, as occurs at Malahide. These waters trend colder in winter and warmer in summer due to the effects of incoming freshwater which in winter is colder and in summer warmer than the corresponding sea temperatures. It can be seen that the temperature of the estuary water increases on low tide when there is freshwater run-off from the Broadmeadow River (Fig.5(a)). Salinity can also have an effect on the solubility of gases in water (Fig.5(b)). Salt water is more dense and becomes saturated with oxygen quicker than freshwater [18]. It would be expected for dissolved oxygen to decrease with increasing salinity, however in this situation the opposite (i.e. High DO at highest salinity) can be observed in Fig.5(b). The reason for this is twofold; the temperature is at its lowest when DO is at its peak and the salinity differences are so small that this relationship is obscured by the tidal influences. The lowest dissolved oxygen concentration over this weekly period (and consistent with other weekly periods) occurs at the lowest salinity. This coincides with the highest temperatures, as previously established above, due to the run off from the "warmer freshwater".

It was found that chlorophyll is positively correlated to the rise and fall of the tides based on salinity (Fig.5(c)). Photosynthesising phytoplankton off the coast of Malahide and other coastal areas move inward toward the land due to tidal movement [20]. It was observed the maximum chlorophyll concentration occurs each day on high tide when salt water and freshwater are mixed . Such daily blooms of chlorophyll could represent "Spring blooms" that occur during the months of April and May. This chlorophyll data corresponds well with the dissolved oxygen data discussed previously.

Throughout the monitoring period turbidity remained relatively constant (between 0-14 NTU), however, a change was observed on 4$^{\text{th}}$ April 2012 (Fig.5(d)), where it increased from the background level to 94.5 NTU. It was discovered that a linked cause of this increase could be a blue green algae (BGA) event which corresponded with other water quality parameters, as well as the onset of stormy, wet weather. The wind blowing seaward moved masses of water from the inner estuary towards the outer estuary and led to the flushing of sediments and BGA from the mudflats present in the outer estuary. Real time data analysis allowed for the verification these observations and the expected marine biological growth.

B. Event monitoring in Poolbeg - a busy estuary

In Poolbeg, on the averaged daily data set regular turbidity events occurred during the deployment period, which led to a jump in turbidity. From this study, relationships between the temporal changes in certain parameters, for instance a correlation between salinity, turbidity and DO were observed. The oscillations that are observed were not caused by water level changes. It was thought that these changes could have resulted from increased rainfall events which was confirmed by the rainfall data (Fig. 4). Other events which regularly led to increased turbidity were linked with ship traffic in Dublin Bay near the deployment site (Fig.6). This was observed numerous times daily as vessels travelled through the port area.

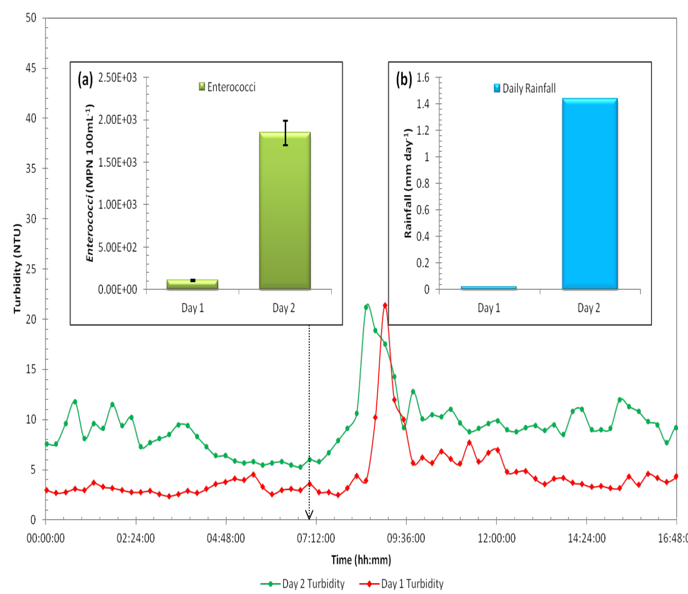
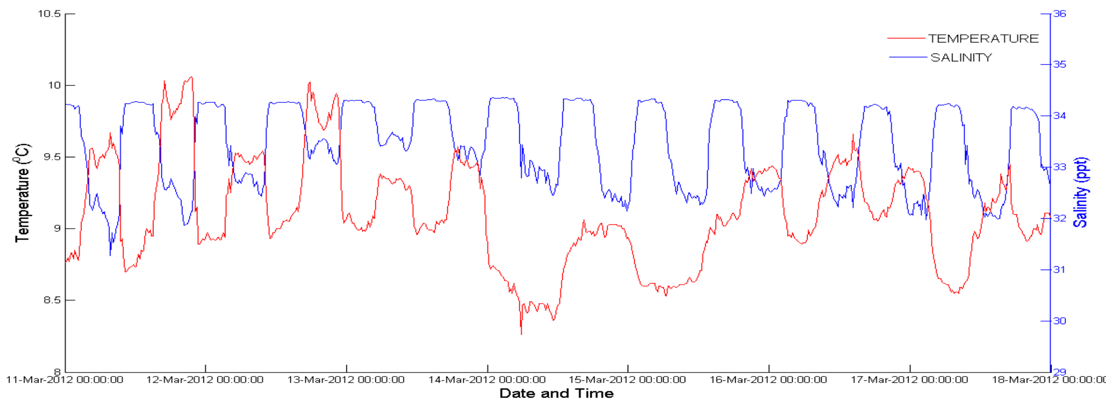
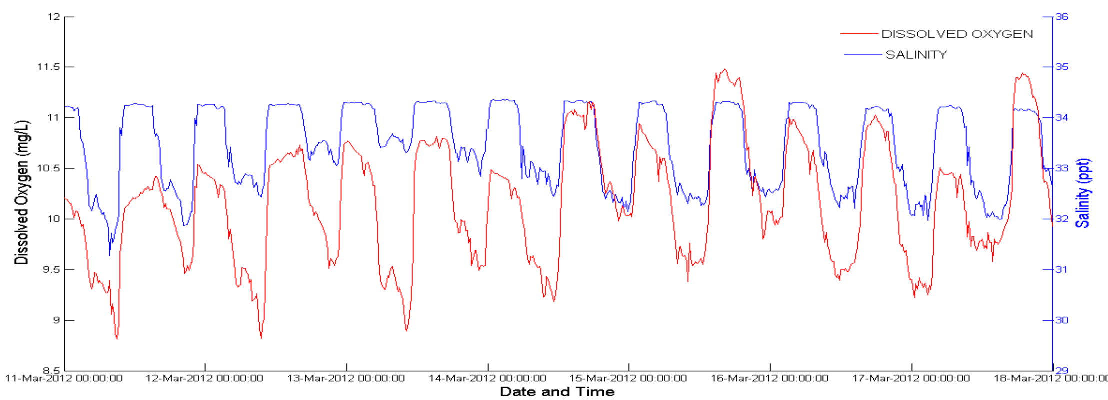


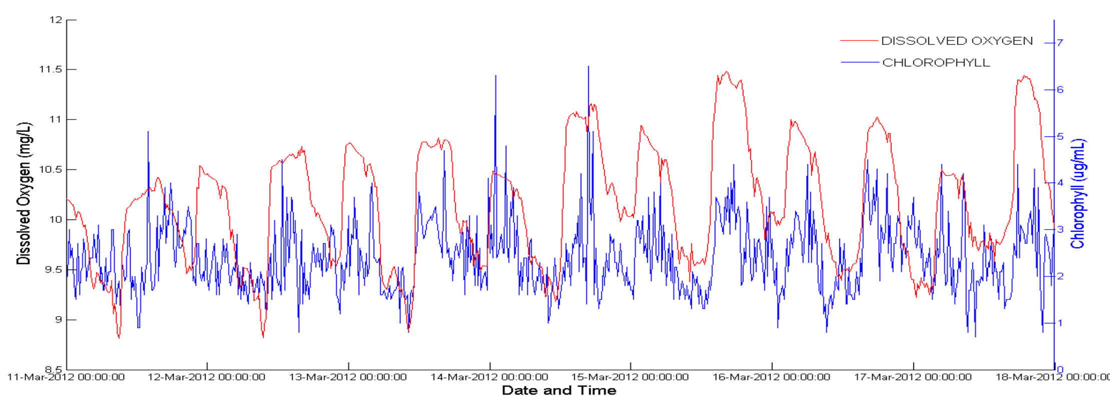
Fig. 4: Rainfall effect on background turbidity levels. Day 1 was during a relatively dry period while Day 2 was after a rainfall event. Inset (a) shows the *Enterococci* levels from the 2 days while inset (b) shows the 24 rainfall data prior to the sample collection. Discrete samples for microbiological analysis were collected on both days between 6:45 and 7:15 am.



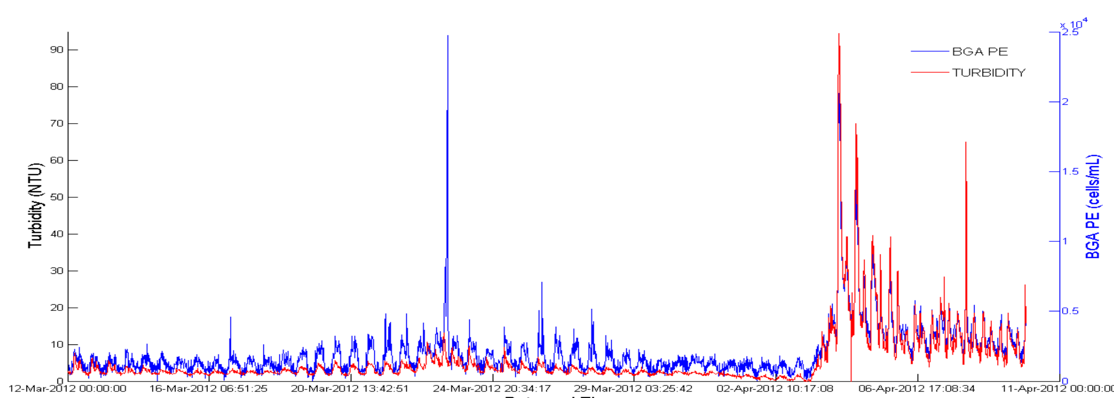
(a)



(b)



(c)



(d)

Fig. 5: Results from the Malahide estuary deployment: (a) salinity and temperature over seven days in Malahide estuary illustrating the effects of the tide and freshwater run-off, (b) dissolved oxygen and salinity overlaid indicating the daily variation, (c) overlay of dissolved oxygen and chlorophyll for a seven day period at a sensor depth of 2.5 m, illustrating the relationship between them during a growth period, (d) turbidity and BGA for a four week period showing the turbidity increase during a bloom event.

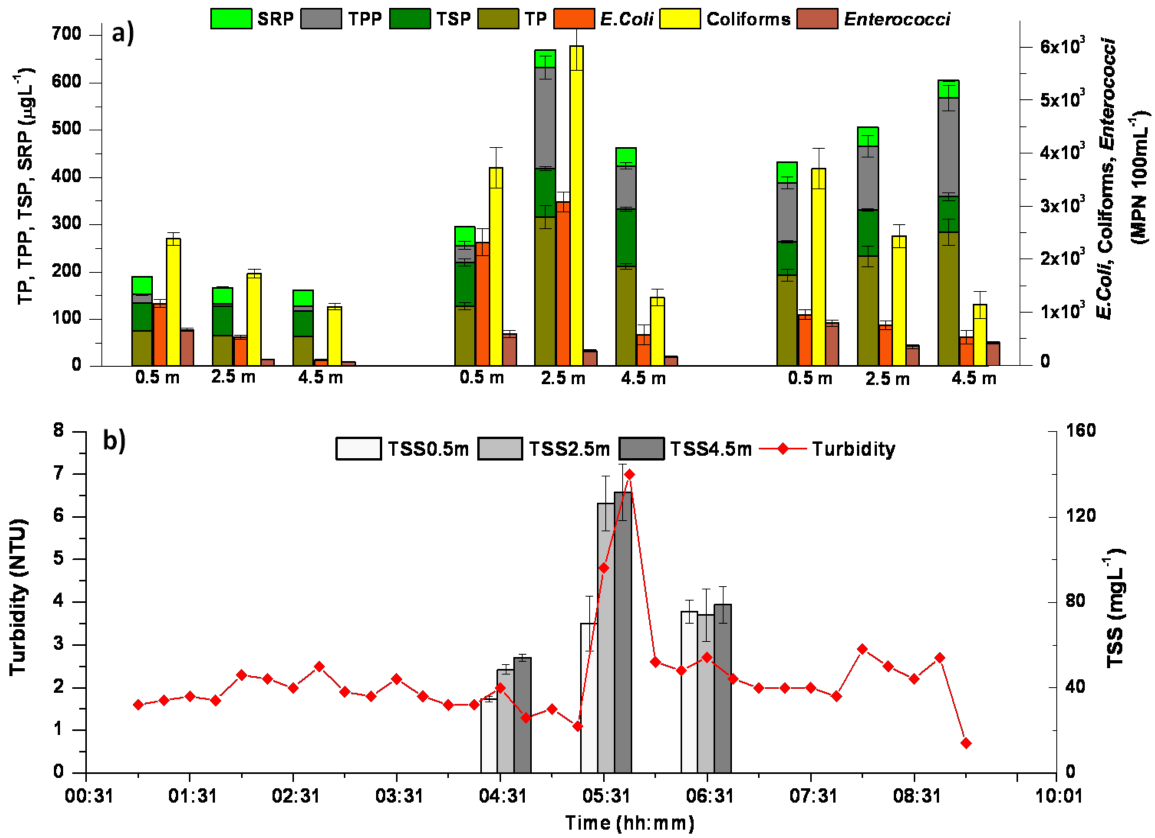


Fig. 6: Data Collected on 15th August 2012: a) Concentration of Solid Reactive Phosphorus (SRP), TPP, Total Suspended Phosphorus (TSP), TP (PO_4-P), *E. coli*, Coliforms and *Enterococci* before the arrival of the ferry (left group), immediately after the arrival (middle group) and 45 min after the arrival (right group); b) Turbidity data, TSS data before (left), at (middle) and 45 mins after (right) the arrival of the ferry. Error bars represent SD of n=3 individual samples collected at the site.

Fig. 4 shows how levels of faecal indicators in the water are elevated (Inset (a)), in association with rises in the background turbidity level. Discrete samples for microbiological analysis were collected on both days between 6:45 am and 7:15 am, with the level of *Enterococci* found to be much increased on the second day. On further investigation it was discovered that, in the intervening day there was large rainfall, as illustrated in Inset (b) of Fig. 4.

A typical ship transit event occurred on the 15th of August 2012, as indicated by the continuous monitoring. Data grab samples were gathered at these times to identify if these events could be used to indicate ideal sampling times. In Fig.6 the lower plot represents a turbidity increase that is linked to a vessel arrival. Samples taken before, during and after this event were analysed for microbial content (*E. coli*, Coliforms and *Enterococci*) and phosphorus (Solid Reactive Phosphorus (SRP), TPP, Total Suspended Phosphorus (TSP), TP (PO_4-P).

A concentration gradient in the water column for microbiological data was observed for the samples collected before the arrival of the first ferry, with higher bacteria densities recorded in the surface water layer (0.5 m), as seen in Fig.6a. This was expected since the bottom layer represents a mixture of the fresh water, from the Liffey river, and the salt water. The fresh water contains higher levels of biological faecal indicators accumulated from run-off and diffuse point pollution [21]. Bedri Z. *et al.* [22] have used a hydro-environmental model to study the impact of the wastewater treatment plant (WWTP) discharges of *E. coli* on the water quality of Dublin Bay. Results from the model which accounted for wind speeds, tidal cycle, density differences within the water column and flow velocities showed that *E. coli* counts at the working site are not affected by the WWTP discharges. Another reason for the presence of the concentration gradient is the increase in osmotic pressure to which bacteria are subjected in the water column. Rich salt water environments cause the water to leave the cell and permeate through the cell wall leaving the bacteria dehydrated, eventually leading to bacterial death. For the data collected, no significant correlation was observed between the faecal indicators data and the P or TSS data, with the exception of *Enterococci*, which was moderately correlated with TSP ($R = 0.429$, $p < 0.05$).

The strongest correlation was found to be between TP and TSS ($R = 0.575$, $p < 0.05$) and TPP and TSS ($R = 0.568$, $p < 0.054$). This suggests that most of the TP enrichment in the water column is attributed to TPP associated with re-suspension of river bed material. It was identified that the major source of TP is associated with light weight sediments from the top layer of the river bed (flocculated organic material with low sheer stress).

V. Conclusion

This challenging project is based on the collection of three years of continuous water quality data, supported by sample analyses for environmental parameters. The work as presented here attempts to better understand the value of continuous monitoring. It is clear from this work that simple continuous measurements of water quality parameters such as temperature, DO, turbidity and salinity can provide valuable information on the activities in estuaries around Dublin. This monitoring, supported by meteorological data, provides a valuable decision support tool which can be utilized to establish suitable water sampling times for the purpose of monitoring compliance, information about the onset of algal blooms, the frequency of pollution events and sources of pollution events among others.

Two scenarios are provided to demonstrate the potential of continuous monitoring e.g. turbidity data as an indicator of a significant change in a system, identifying ideal times for sample collection as part of a monitoring programme; and the value of salinity in identifying periods of freshwater input to the estuary, as an indicator of a potential flooding event. These data do not confirm events but rather inform a decision maker, assisting in the environmental management decision process.

The data obtained in real-time can also be valuable in monitoring the performance of the sensing system, whereby the data can identify when sensors require maintenance in a timely manner, so that the integrity of the data and monitoring system can be maintained.

The SmartBay-SmartCity project in Dublin, plans to expand the sensor network in the coming year to include additional sites in the Bay. The network will include further visual sensing technologies, multi-modal data analysis and prediction tools to provide stakeholders or users with valuable information for a variety of applications in areas of tourism, water quality, security or flood management.

Acknowledgements

The authors acknowledge the funding of this research through the Beaufort Marine Research Award, carried out under the Sea Change Strategy and the Strategy for Science Technology and Innovation (2006-2013), with the support of the Marine Institute, funded under the Marine Research Sub-Programme of the National Development Plan 2007-2013. Also, QUESTOR Research Centre under grant DCU8/10/2013 and Science Foundation Ireland under grant 07/CE/I1147. The authors also wish to thank the staff at Poolbeg marina and Malahide marina for permission, assistance and access to the deployment location and marina facilities.

References

[1] R. Greenwood, J. Webster, and F. Regan, "Sustainable Water: Chemical Science Priorities. Chap 4 Water monitoring", *Royal Society of Chemistry Report*, http://www.rsc.org/images/waterreport_tcm18-108403.pdf, 2007.

[2] J. Grath, R. Ward, A. Scheidleder, and P. Quevauviller, "Report on EU guidance on groundwater monitoring developed under the common implementation strategy of the water framework directive", *J. Environ. Monit.*, **9**, 2007, pp. 1162-1175.

[3] A. Lawlor, F. Regan, J. Torres, B. O'Flynn and J. Wallace, "DEPLOY: A long term deployment of a water quality sensor monitoring system", *Sensor Review*, **32**, 1, 2012, pp. 29-38.

[4] C. Albaladejo, *et. al.*,"Wireless sensor networks for oceanographic monitoring: A systematic review", *Sensors*, **10**, 7, 2010, pp. 6948-6968.

[5] P. W. Rundel, E. A. Graham, M. F. Allen, J. C. Fisher and T. C. Harmon, "Environmental sensor networks in ecological research", *New Phytol.*, **182**, 3, 2009, pp. 589-607.

[6] S. M. Glenn, T. D. Dickey, B. Parker, and W. Boicourt, "Long-term real-time coastal ocean observation networks", *Oceanography*, **13**, 1, 2000, pp. 24-34.

[7] T. S. Moore, *et. al.*, "Marine chemical technology and sensors for marine waters: potentials and limits", *Annual Review of Marine Science*, **1**, 2009, pp. 91-115.

[8] T. Voigt, *et. al.*, "Sensor networking in aquatic environments-experiences and new challenges", *32nd. IEEE Conference on Local Computer Networks*, 2007, pp. 793-798.

[9] B. O'Flynn, *et. al.*, " Experiences and recommendations in deploying a real-time, water quality monitoring system", *Meas. Sci. Technol.*, **21**, 2010, pp. 124004-124008.

[10] F. Regan, A. Lawlor and A. McCarthy"SmartCoast project- SmartWater quality monitoring system", *STRIVE Report Series No. 30*, EPA, 2009.

[11] F. Regan, A. Lawlor, B. O'Flynn and J. Wallace"DEPLOY: Smart demonstration of online water quality monitoring on the River Lee, Cork, Ireland", *STRIVE Report Series No. 82*, EPA, 2011.

[12] S. O'Boyle and J. Silke, "A review of phytoplankton ecology in estuarine and coastal waters around Ireland", *J. Plankton Res.*, **32**, 1, 2010, pp. 99-118.

[13] R. Greene, "Around and about Malahide", *Fingal County Libraries, Co. Dublin*, 2009.

[14] D. W. Connell, "Basic Concepts of Environmental Chemistry", *Lewis Publishers, CRC Press*, 1^{st} Ed., 1997.

[15] S. Roth and J. G. Wilson, "Functional analysis by trophic guilds of macrobenthic community structure in Dublin Bay, Ireland", *J. Exp. Mar. Biol. Ecol.*, **222**, 1-2, 1998, pp. 195-217.

[16] R. J. Wagner, R. W. Boulger, C. J. Oblinger, Jr., and B. A. Smith "Guidelines and Standard Procedures for Continuous Water-Quality Monitors - Station Operation, Record Computation, and Data Reporting", *U.S. Geological Survey Techniques and Methods*, http://pubs.water.usgs.gov/tm1d3, 2006.

[17] J. Murphy and J. P. Riley, "A Single Solution Method for the Determination of Soluble Phosphate in Sea Water", *J. Mar. Biol. Assoc.*, **37**, 1958, pp. 9-14.

[18] American Public Health Association, American Water Works Association, and Water Environment Federation, "Standard methods for the examination of water and wastewater", *American Public Health Association, Inc.*, 18^{th} Ed., 1992 .

[19] J. S. Horsburgh, A. Spackman Jones, D. K. Stevens, D. G.Tarboton, and N.O.Mesner,"A sensor network for high frequency estimation of water quality constituent fluxes using surrogates", *Environmental Modelling & Software*, **25**, 9, 2010, pp. 1031-1044.

[20] F. Regan, *et. al.*, "A demonstration of wireless sensing for long term monitoring of water quality", *The 4th IEEE International Workshop on Practical Issues in Building Sensor Network Applications (SenseApp 2009)*, 2009, pp. 819-825.

[21] B. M. Steets and P. A. Holden, "A mechanistic model of runoff-associated fecal coliform fate and transport through a coastal lagoon", *Water Research*, **37**, 3, 2003, pp. 589-608.

[22] Z. Bedri, M. Bruen, A. Dowley, and B. Masterson, "A Three-Dimensional Hydro-Environmental Model of Dublin Bay", *Environmental Modeling & Assesment*, **16**, 4, 2011, pp. 369-384.