USE OF WIRELESS SENSOR NETWORKS TO STUDY WATER QUALITY IN RIVERS AND AIR QUALITY

BSB-884 - "JOINT MONITORING FOR ENVIRONMENTAL PROTECTION IN BSB COUNTRIES"- BSB ECO MONITORING

WORK PACKAGE 1

SMART ENVIRONMENTAL MONITORING AND OBSERVATION

Deliverable D.T1.2.1

Plovdiv, 30th December 2020

Contents

INTRODUCTION

Recent advances in communication and sensor technology have catalyzed progress in remote monitoring capabilities for water and air quality. As a result, the ability to characterize dynamic hydrologic properties at adequate temporal and spatial scales has greatly improved. These advances have led to improved statistical and mechanistic modeling in monitoring of water quality trends at local, watershed and regional scales for freshwater, estuarine and marine ecosystems. In addition, they have greatly enhanced rapid (e.g., real-time) detection of hydrologic variability, recognized as a critical need for early warning systems and rapid response to harmful algal bloom events.

Air supplies us with oxygen that is essential for our bodies to live. Air is 99.9% nitrogen, oxygen, water vapor, and inert gases.

The monitoring of pollution level in urban areas must be considered one of the most important services for the citizens, indeed, the presence of high levels of pollutants are correlated with respiratory illnesses such as bronchitis, asthma, and chronic obstructive pulmonary disease that represent the cause of death for 12 million of peoples according to the World Health Organization [1]. Typically the air pollution is monitored by expensive station, usually equipped with multiple instruments (worth more than 30,000 €) and located in fixed point in an urban areas. Moreover, complex and repetitive calibration and maintenance operations are requested in order to obtain highly accurate measurements. Thus, few points of measurements are often available, not ensuring the awareness of the air quality in places not close to the measurement station. In order to obtain a distributed information on air pollution some solutions are adopted such as the use of air-quality mobile stations, passive samplers or models. In the first case, mobile stations are also very expansive as fixed stations and in most cases; they do not guarantee to reach a sufficient level of information to make a good density of spatial sampling. The passive samplers are less expensive than fixed and mobile stations, nevertheless they are not able to appreciate episodes of pollution with a high dynamics. Finally, the adoption of models requires a high level of knowledge and data that are not easily available in the most cases [2].

Recent technological advances in the field of embedded electronic and IoT and wireless sensor networks (WSN) lead to the development and proposal of low-cost sensors (~150€-250€) for pollution monitoring and wireless/wired interfaces (GPRS, Wi-Fi, LAN, LoraWan), enabling people [3] to share information about the urban air quality.

Development in the technology of sensor such as Micro Electro Mechanical Systems (MEMS), wireless communications, embedded systems, distributed processing and wireless sensor applications have contributed a large transformation in Wireless Sensor Network (WSN) recently. It assists and improves work performance in both the field of industry and our daily life. Wireless Sensor Network has been widely used in many areas especially for surveillance and monitoring in agriculture and habitat monitoring. Environment monitoring has become an important field of control and protection, providing real-time system and control communication with the physical world. An intelligent and smart Wireless Sensor Network system can gather and process a large amount of data from the beginning of the monitoring and manage air quality, the conditions of traffic, to weather situations.

In this paper, we discuss and review wireless sensor network applications for environmental monitoring of air quality and water river quality.

WIRELESS SENSOR NETWORKS

Wireless Sensor Networks (WSNs) can be defined as a self-configured and infrastructure-less wireless networks to monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants, water parameters and to cooperatively pass their data through the network to a main location or sink where the data can be observed and analyzed. A sink or base station acts like an interface between users and the network. One can retrieve required information from the network by injecting queries and gathering results from the sink. Typically a wireless sensor network contains hundreds of thousands of sensor nodes. The sensor nodes can communicate among themselves using radio signals. A wireless sensor node is equipped with sensing and computing devices, radio transceivers and power components. The individual nodes in a wireless sensor network (WSN) are inherently resource constrained: they have limited processing speed, storage capacity, and communication bandwidth. After the sensor nodes are deployed, they are responsible for self-organizing an appropriate network infrastructure often with multi-hop communication with them. Then the onboard sensors start collecting information of interest. Wireless sensor devices also respond to queries sent from a "control site" to perform specific instructions or provide sensing samples. The working mode of the sensor nodes may be either continuous or event driven. Global Positioning System (GPS) and local positioning algorithms can be used to obtain location and positioning information. Wireless sensor devices can be equipped with actuators to "act" upon certain conditions. These networks are sometimes more specifically referred as Wireless Sensor and Actuator Networks as described in (Akkaya et al., 2005).

Wireless sensor networks (WSNs) enable new applications and require non-conventional paradigms for protocol design due to several constraints. Owing to the requirement for low device complexity together with low energy consumption (i.e. long network lifetime), a proper balance between communication and signal/data processing capabilities must be found. This motivates a huge effort in research activities, standardization process, and industrial investments on this field since the last decade (Chiara et. al. 2009). At present time, most of the research on WSNs has concentrated on the design of energy- and computationally efficient algorithms and protocols, and the application domain has been restricted to simple data-oriented monitoring and reporting applications (Labrador et. al. 2009). The authors in (Chen et al., 2011) propose a Cable Mode Transition (CMT) algorithm, which determines the minimal number of active sensors to maintain K-coverage of a terrain as well as K-connectivity of the network. Specifically, it allocates periods of inactivity for cable sensors without affecting the coverage and connectivity requirements of the network based only on local information. In (Cheng et al., 2011), a delay-aware data collection network structure for wireless sensor networks is proposed. The objective of the proposed network structure is to minimize delays in the data collection processes of wireless sensor networks which extends the lifetime of the network. In (Matin et al., 2011), the authors have considered relay nodes to mitigate the network geometric deficiencies and used Particle Swarm Optimization (PSO) based algorithms to locate the optimal sink location with respect to those relay nodes to overcome the lifetime challenge. Energy efficient communication has also been addressed in (Paul et al., 2011; Fabbri et al. 2009). In (Paul et al., 2011), the authors proposed a geometrical solution for locating the optimum sink placement for maximizing the network lifetime. Most of the time, the research on wireless sensor networks have considered homogeneous sensor nodes. However, nowadays researchers have focused on heterogeneous sensor networks where the sensor nodes are unlike to each other in terms of their energy. In (Han et al., 2010), the authors addresses the problem of deploying relay nodes to provide fault tolerance with higher network connectivity in heterogeneous wireless sensor networks, where sensor nodes possess different transmission radii. New network architectures with heterogeneous devices and the recent advancement in this technology eliminate the current limitations and expand the spectrum of possible applications for WSNs considerably and all these are changing very rapidly.

Applications of wireless sensor network Wireless sensor networks have gained considerable popularity due to their flexibility in solving problems in different application domains and have the potential to change our lives

Overview of Wireless Sensor Network 5 in many different ways. WSNs have been successfully applied in various application domains (Akyildiz et al. 2002; Bharathidasan et al., 2001), (Yick et al., 2008; Boukerche, 2009), (Sohraby et al., 2007), and (Chiara et al., 2009;Verdone et al., 2008), such as: Military applications: Wireless sensor networks be

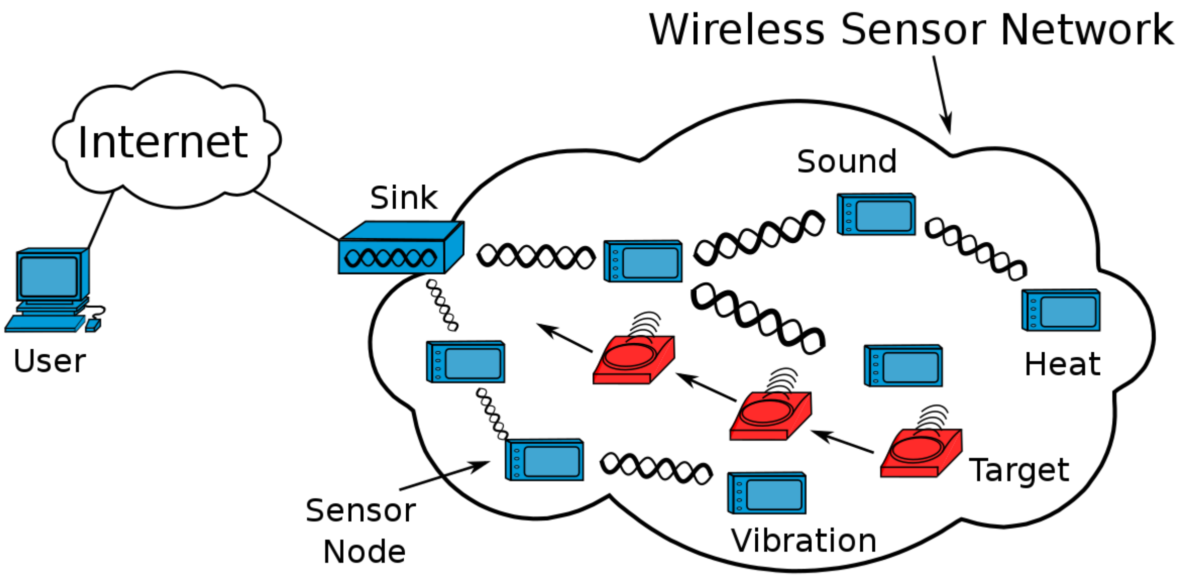

Fig.1 A typical wireless sensor network

Likely an integral part of military command, control, communications, computing, intelligence, battlefield surveillance, reconnaissance and targeting systems. Area monitoring: In area monitoring, the sensor nodes are deployed over a region where some phenomenon is to be monitored. When the sensors detect the event being monitored (heat, pressure etc), the event is reported to one of the base stations, which then takes appropriate action. Transportation: Real-time traffic information is being collected by WSNs to later feed transportation models and alert drivers of congestion and traffic problems. Health applications: Some of the health applications for sensor networks are supporting interfaces for the disabled, integrated patient monitoring, diagnostics, and drug administration in hospitals, tele-monitoring of human physiological data, and tracking & monitoring doctors or patients inside a hospital. Environmental sensing: The term Environmental Sensor Networks has developed to cover many applications of WSNs to earth science research. This includes sensing volcanoes, oceans, glaciers, forests etc. Some other major areas are listed below:

- Air pollution monitoring
- Forest fires detection
- Greenhouse monitoring
- Landslide detection

- Water monitoring

Structural monitoring: Wireless sensors can be utilized to monitor the movement within buildings and infrastructure such as bridges, flyovers, embankments, tunnels etc enabling Engineering practices to monitor assets remotely without the need for costly site visits. Industrial monitoring: Wireless sensor networks have been developed for machinery condition-based maintenance (CBM) as they offer significant cost savings and enable new functionalities. In wired systems, the installation of enough sensors is often limited by the cost of wiring. Agricultural sector: using a wireless network frees the farmer from the maintenance of wiring in a difficult environment. Irrigation automation enables more efficient water use and reduces waste.

Structure of a wireless sensor network Structure of a Wireless Sensor Network includes different topologies for radio communications networks. A short discussion of the network topologies that apply to wireless sensor networks are outlined below:

4.1. Star network (single point-to-multipoint) (Wilson, 2005) A star network is a communications topology where a single base station can send and/or receive a message to a number of remote nodes. The remote nodes are not permitted to send messages to each other. The advantage of this type of network for wireless sensor networks includes simplicity, ability to keep the remote node's power consumption to a minimum. It also allows low latency communications between the remote node and the base station. The disadvantage of such a network is that the base station must be within radio transmission range of all the individual nodes and is not as robust as other networks due to its dependency on a single node to manage the network.

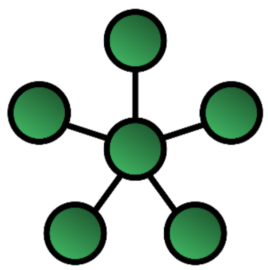

Fig.2 A star network topology

4.2. Mesh network (Wilson, 2005) A mesh network allows transmitting data to one node to other node in the network that is within its radio transmission range. This allows for what is known as multi-hop communications, that is, if a node wants to send a message to another node that is out of radio communications range, it can use an intermediate node to forward the message to the desired node. This network topology has the advantage of redundancy and scalability. If an individual node fails, a remote node still can communicate to any other node in its range, which in turn, can forward the message to the desired location. In addition, the range of the network is not necessarily limited by the range in between single nodes; it can simply be extended by adding more nodes to the system. The disadvantage of this type of network is in power consumption for the nodes that implement the multi-hop communications are generally higher than for the nodes that don't have this capability, often limiting the battery life. Additionally, as the number of communication hops to a destination increases, the time to deliver the message also increases, especially if low power operation of the nodes is a requirement

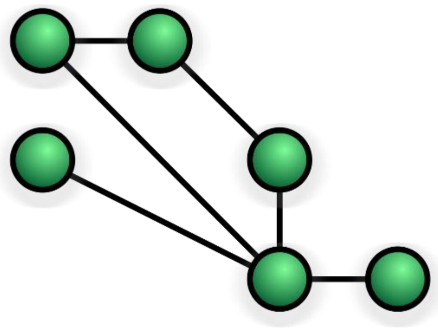

Fig.3 A Mesh network topology

4.3. Hybrid star – Mesh network (Wilson, 2005)

A hybrid between the star and mesh network provides a robust and versatile communications network, while maintaining the ability to keep the wireless sensor nodes power consumption to a minimum. In this network topology, the sensor nodes with lowest power are not enabled with the ability to forward messages. This allows for minimal power consumption to be maintained. However, other nodes on the network are enabled with multi-hop capability, allowing them to forward messages from the low power nodes to other nodes on the network. Generally, the nodes with the multi-hop capability are higher power, and if possible, are often plugged into the electrical mains line. This is the topology implemented by the up and coming mesh-networking standard known as ZigBee.

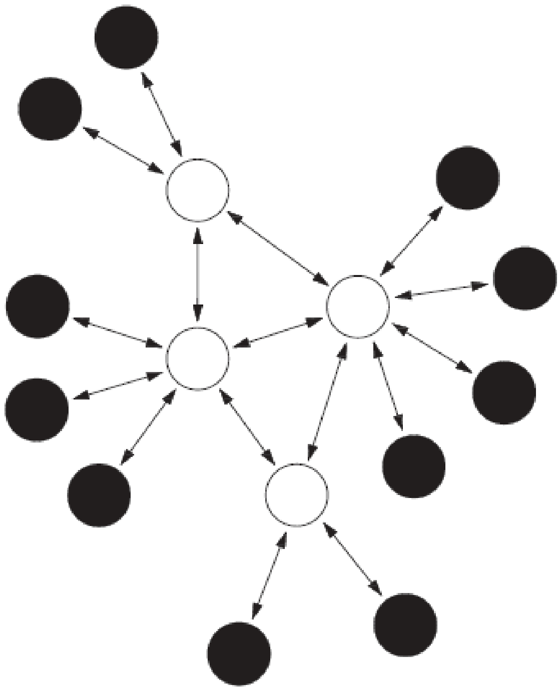

Fig.4 A Hybrid Star – Mesh network topology

5. Structure of a wireless sensor node

A sensor node is made up of four basic components such as sensing unit, processing unit, transceiver unit and a power unit which is shown in Fig. 5. It also has application dependent additional components such as a location finding system, a power generator and a mobilizer. Sensing units are usually composed of two subunits: sensors and analogue to digital converters (ADCs) (Akyildiz et al., 2002). The analogue signals produced by the sensors are converted to digital signals by the ADC, and then fed into the processing unit. The processing unit is generally associated with a small storage unit and it can manage the procedures that make the sensor node collaborate with the other nodes to carry out the assigned sensing tasks. A ransceiver unit connects the node to the network. One of the most important components of a sensor node is the power unit. Power units can be supported by a power scavenging unit such as solar cells. The other subunits, of the node are application dependent. A functional block diagram of a versatile wireless sensing node is provided in Fig. 6. Modular design approach provides a flexible and versatile platform to address the needs of a wide variety of applications. For example, depending on the sensors to be deployed, the signal conditioning block can be re-programmed or replaced. This allows for a wide variety of different sensors to be used with the wireless sensing node. Similarly, the radio link may be swapped out as required for a given applications' wireless range requirement and the need for bidirectional communications.

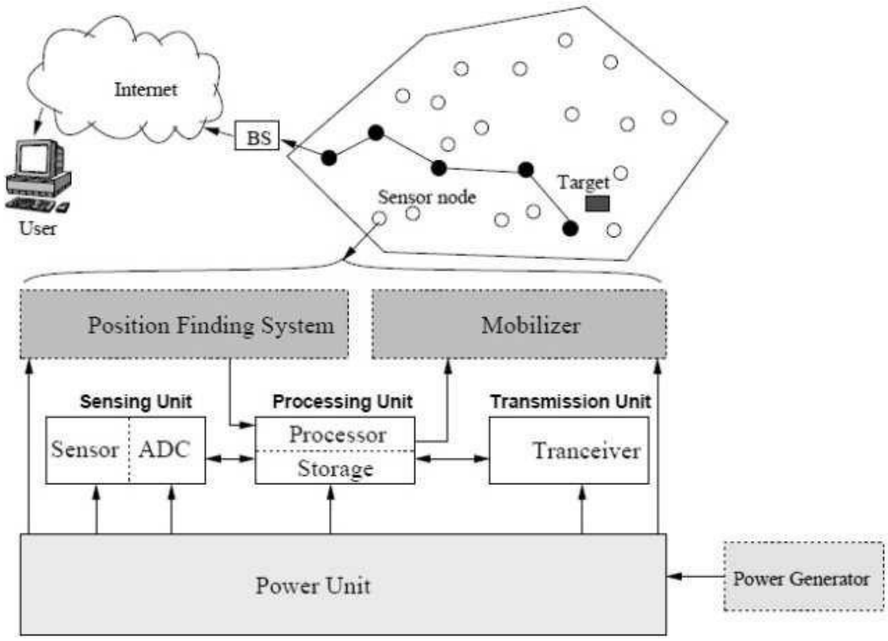

Fig.5 The components of a sensor node

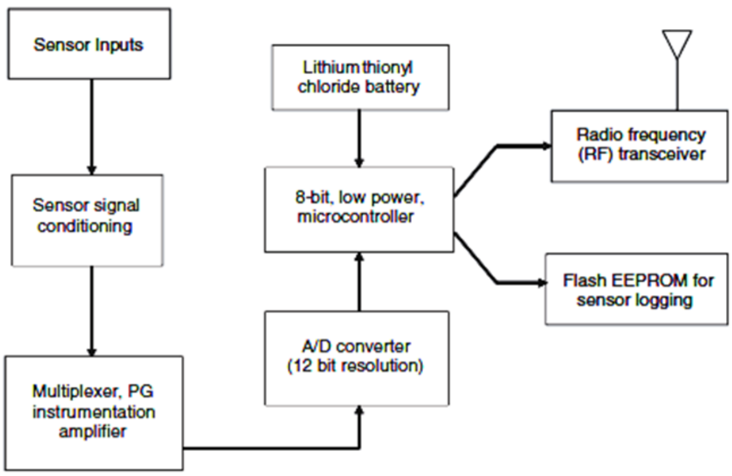

Fig.6 Functional block diagram of a sensor node

Using flash memory, the remote nodes acquire data on command from a base station, or by an event sensed by one or more inputs to the node. Moreover, the embedded firmware can be upgraded through the wireless network in the field. The microprocessor has a number of functions including:

Managing data collection from the sensors:

- performing power management functions
- interfacing the sensor data to the physical radio layer
- managing the radio network protocol

A key aspect of any wireless sensing node is to minimize the power consumed by the system. Usually, the radio subsystem requires the largest amount of power. Therefore, data is sent over the radio network only when it is required. An algorithm is to be loaded into the node to determine when to send data based on the sensed event. Furthermore, it is important to minimize the power consumed by the sensor itself. Therefore, the hardware should be designed to allow the microprocessor to judiciously control power to the radio, sensor, and sensor signal conditioner (Akyildiz et al., 2002).

AIR QUALITY MONITORING WITH WIRELESS SENSOR NODES

Particulate matter (PM10 and PM2.5)

Particulate matter, also known as particle pollution or PM, is a term that describes extremely small solid particles and liquid droplets suspended in air. Particulate matter can be made up of a variety of components including nitrates, sulfates, organic chemicals, metals, soil or dust particles, and allergens (such as fragments of pollen or mould spores). Particle pollution mainly comes from motor vehicles, wood burning heaters and industry. During bushfires or dust storms, particle pollution can reach extremely high concentrations.

The size of particles affects their potential to cause health problems:

- PM10 (particles with a diameter of 10 micrometres or less): these particles are small enough to pass through the throat and nose and enter the lungs. Once inhaled, these particles can affect the heart and lungs and cause serious health effects.
- PM2.5 (particles with a diameter of 2.5 micrometres or less): these particles are so small they can get deep into the lungs and into the bloodstream. There is sufficient evidence that exposure to PM2.5 over long periods (years) can cause adverse health effects. Note that PM10 includes PM2.5.
- PM1 – particles <1 µm in size. Examples: dust, combustion particles*, bacteria and viruses.

Potential health effects from exposure to particulate matter:

There are many health effects from exposure to particulate matter. Numerous studies have showed associations between exposure to particles and increased hospital admissions as well as death from heart or lung diseases. Despite extensive epidemiological research, there is currently no evidence of a threshold below which exposure to particulate matter does not cause any health effects. Health effects can occur after both short and long-term exposure to particulate matter.

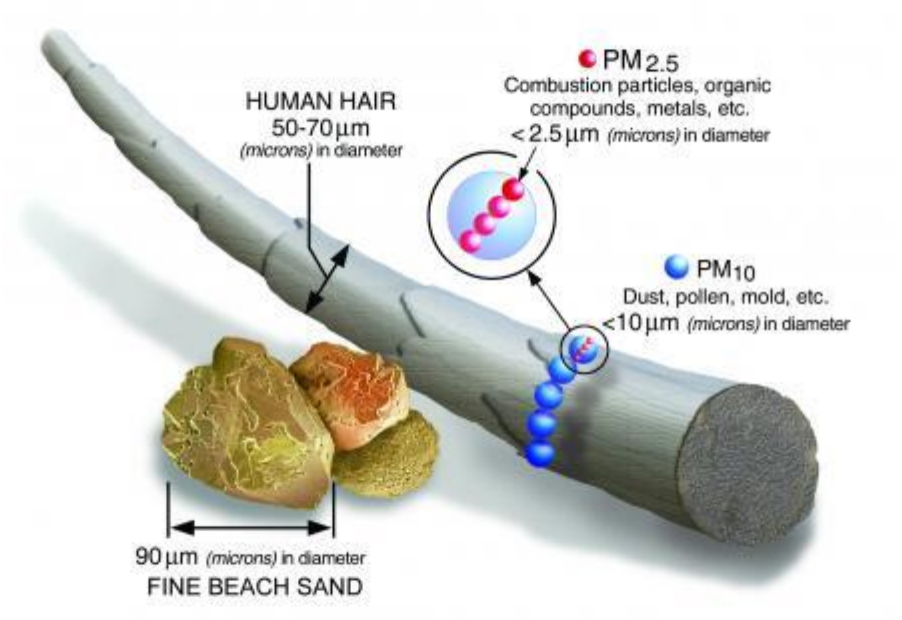

Fig.7 Size comparisons for PM particles

Short-term and long-term exposure is thought to have different mechanisms of effect. Short-term exposure appears to exacerbate pre-existing diseases while long-term exposure most likely causes disease and increases the rate of progression.

Short-term exposure (hours to days) can lead to:

- irritated eyes, nose and throat
- worsening asthma and lung diseases such as chronic bronchitis (also called chronic obstructive pulmonary disease or COPD)
- heart attacks and arrhythmias (irregular heart beat) in people with heart disease
- Increases in hospital admissions and premature death due to diseases of the respiratory and cardiovascular systems.

Long-term exposure (many years) can lead to:

- reduced lung function
- development of cardiovascular and respiratory diseases
- increased rate of disease progression

- Reduction in life expectancy.

Sources of PM

These particles come in many sizes and shapes and can be made up of hundreds of different chemicals.

Some are emitted directly from a source, such as construction sites, unpaved roads, fields, smokestacks or fires.

Most particles form in the atmosphere because of complex reactions of chemicals such as sulfur dioxide and nitrogen oxides, which are pollutants emitted from power plants, industries and automobiles.

PARTICULATE MATTER SENSING FOR AIR QUALITY MEASUREMENTS

Particulate Matter, abbreviated as 'PM', is a mixture of airborne solid particles and liquid droplets that can be inhaled and may cause serious health problems. PM includes particles with different characteristics – i.e. shape, optical properties, size and composition ¬– but it is most commonly divided into sub-categories based on the particle size information. Different PM categories are usually reported under the common nomenclature of PMx, where 'x' defines the maximum particle diameter in the airborne particle mixture or 'aerosol'. For example, PM2.5 defines inhalable particles with a diameter of generally 2.5 micrometers and smaller, PM10 particles with a diameter of 10 micrometers and smaller, and so forth. National governments as important monitoring levels have historically identified the specific PM categories of PM10 and PM2.5 in order to assess the quality of the air we breathe, because PM10 particles irritate exposed mucous such as the eyes and throat and PM2.5 particles travel all the way through the lungs into the alveoli. New categories like PM1.0 and PM4.0 are also finding their way into air quality monitoring devices as these new outputs provide additional information to the traditional PM10 and PM2.5 levels, enabling a better particle pollution analysis and the development of new device-specific actions based on the detected aerosol type (e.g. house dust vs. smoke).

The common definition of PM includes particles that are no smaller than 100 nanometers in size. Particles smaller than 100 nm are instead reported as 'ultrafine particles' or 'UFPs' and are not covered in this article. Within the above-mentioned PM definition, which thus includes particles from 0.1 to 10 micrometers in size, the smaller the particles are, the deeper they can penetrate through our respiratory system and into our bloodstream, posing a higher hazard to our health. The World Health Organization (WHO) reports airborne particulate matter as a Group 1 carcinogen and as the biggest environmental risk to health, with responsibility for about one in every nine deaths annually. Fig. 1 shows the size range of common pollutant sources, including filtration technologies used for the removal of such contaminants (adapted from John Wiley and Sons, Best Practices Guide to Residential Construction, 2006).

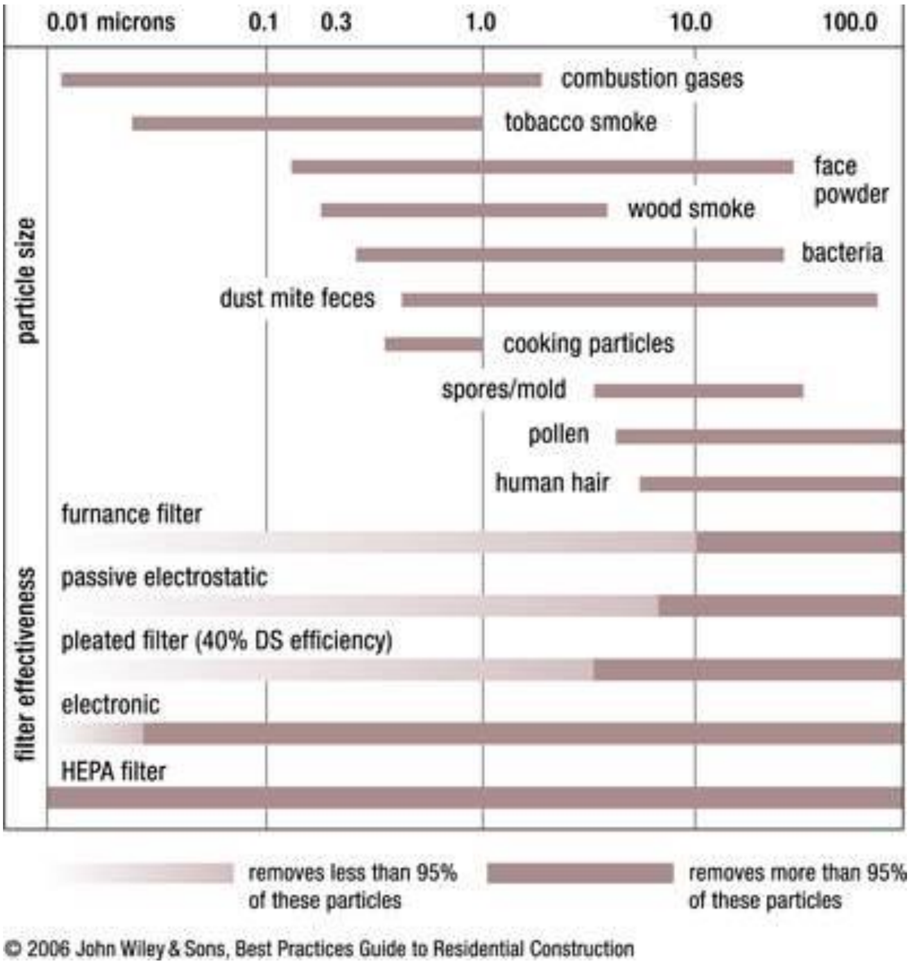

Fig.8 Size range of common pollutant sources (adapted from John Wiley and Sons, Best Practices Guide to Residential Construction, 2006).

Historically, PM values are measured as 'mass concentration' in μg/m3. The reason behind this is that the traditional and most accurate way to measure PM is the gravimetric method. This procedure makes use of a pre-weighed filter to collect ambient particles that are physically pre-sorted based on their size (e.g. all particles below 2.5 μm are let in). At the end of the sampling period, usually 24 hours, the filter is weighed to determine the total accumulated PM mass in μg. Mass concentration is then obtained by dividing the mass increase of the filter by the 24-hour total volume of air that passed through the filter, resulting in a value in μg/m3. Although gravimetric methods are long established as the most accurate way of determining mass concentration, they have some practical limitations to their diffusion in everyday applications: these instruments are bulky, very expensive, they process only one PM size per measurement (e.g. PM2.5), real-time sampling is not possible, and they cannot output the particle number count.

For these reasons, real-time optical particle counters (OPCs) have progressively found their way into the air quality monitoring market. These instruments are based on different optical principles, typically scattering or absorption, with light scattering being the most commonly used. In these OPCs, the particle passes through the light source (usually a laser beam) and causes scattering (or absorption) of the incoming light, which is then detected by a photodiode and converted into real-time particle count and mass concentration values.

Currently, optical detection is the most widespread technique due to its ease of use and unbeatable cost-performance ratio. In recent years, OPCs have become small enough to be integrated into air conditioners, air quality monitors and air purifiers, and are used to regulate and control air quality in households, cars and outdoor environments.

Although the basic principle of OPCs might seem simple at first from an implementation point of view, not all OPCs perform in the same way and the quality of their measurement depends greatly on the engineering and design of such devices. The optical principle works very well in terms of particle counting, but as these devices are used mainly for the estimation of the PM mass concentration, they will be susceptible to estimation errors due to the different optical properties of the particles (e.g. shape and color) and different mass densities. The quality of the mass estimation will thus vary highly depending on the manufacturer algorithm used to convert the measured optical signal into PM mass concentration. In addition, the internal airflow engineering has a high impact on the accuracy and drift of these sensors as particles can accumulate easily on their optical elements (laser, photodiode, and beam-dump) and degrade their output over time if they are not properly engineered.

Working principle

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Particle Composition Recognition

As mentioned above, the manufacturer's algorithms, together with a proper front-end electronics design, make a fundamental difference in the estimation of mass concentration from the detected scattered light.

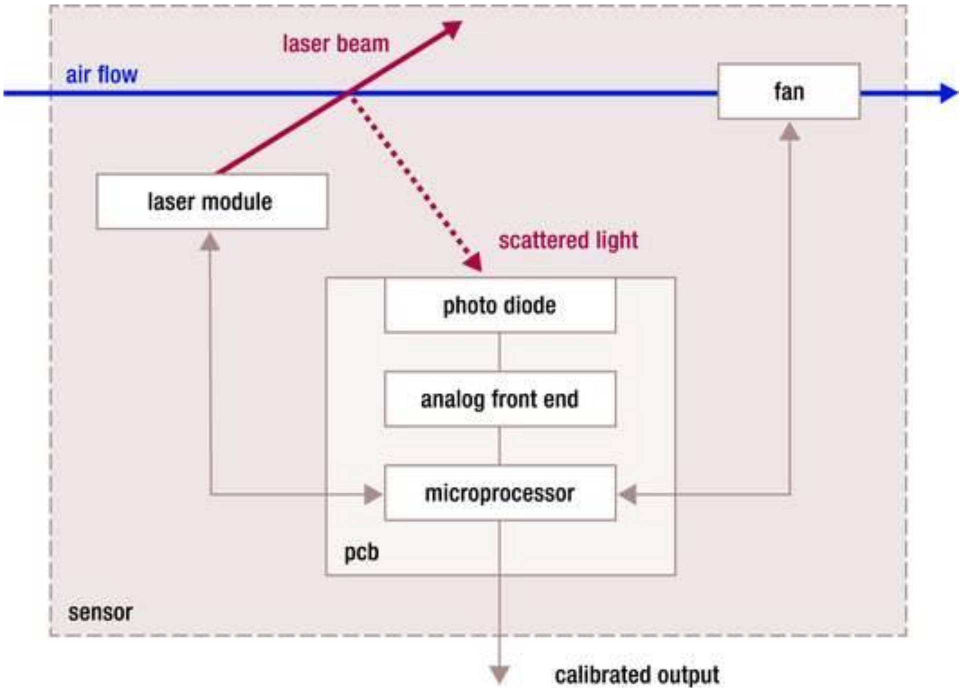

Fig.9: Block diagram SPS30 (Source: Sensirion)

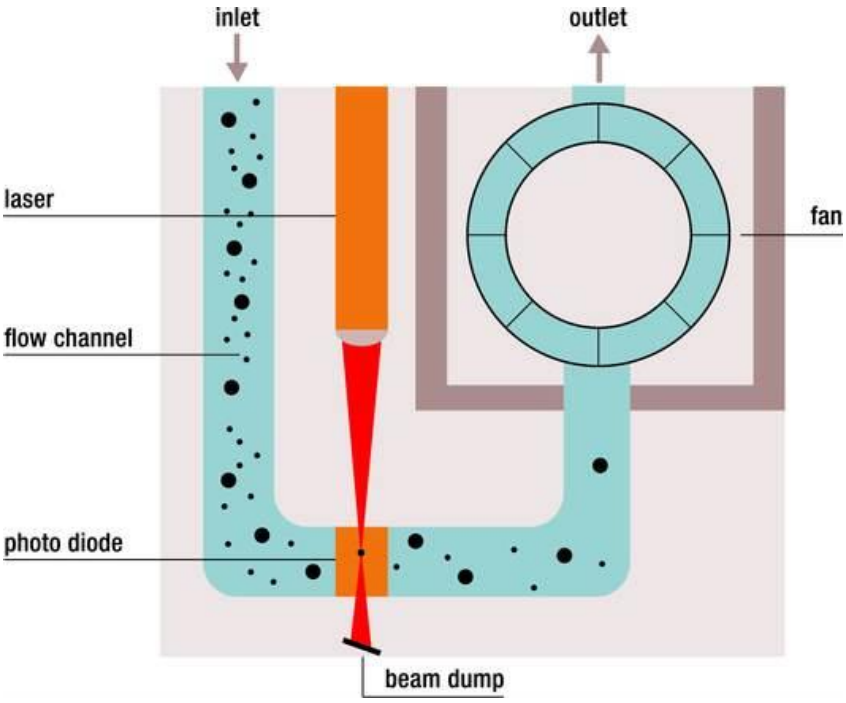

Fig.10 Working principle (Source: Sensirion)

Most low-cost PM sensors on the market assume a constant mass density in calibration and calculate the mass concentration by multiplying the detected particle count by this mass density. This assumption only works if the sensor measures a single particle type (for instance, tobacco smoke), but in reality we find many different particle types with many different optical properties in everyday life, from 'heavy' house dust to 'light' combustion particles (see Fig 4). Sensirion's proprietary algorithms use an advanced approach that allows a proper estimation of the mass concentration, regardless of the particle type measured. In addition, such an approach enables a correct estimation of the size bins. In addition, an additional bin output is provided in contrast to most state-of-the-art consumer PM sensors on the market – PM4.0. The increased accuracy for different aerosols and the higher resolution on the number of bins allows users to develop new use cases based on particle composition recognition. Fig. 5 shows a practical demonstration of such a feature, using Sensirion's Control Center software. The bar charts show the real-time measured mass concentration bins, measured with an SPS30. The left chart shows a live measurement of match smoke, clearly richer in smaller particles. The right chart shows a measurement from Arizona dust, clearly richer in bigger particles. This simple but effective experiment highlights the value of the SPS30 advanced binning feature and the potential for the development of new applications based on particle composition detection.

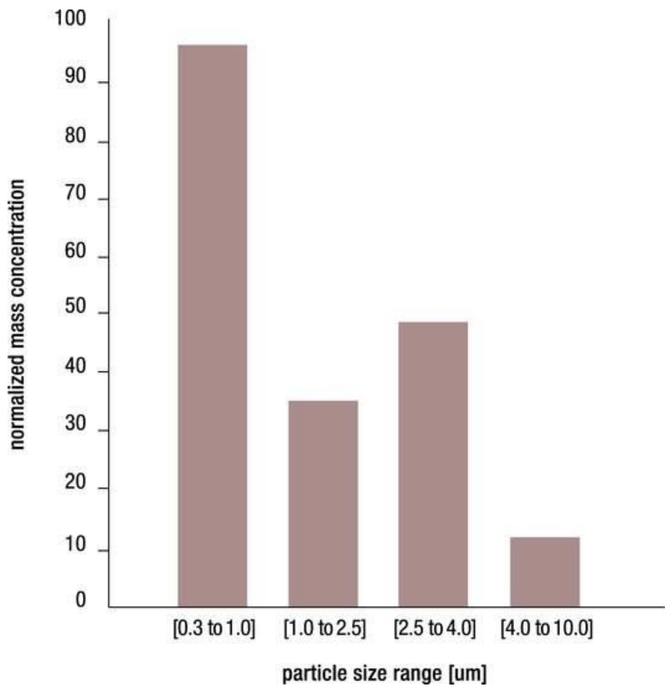

Fig.11 Particle composition of smoke (Source: Sensirion)

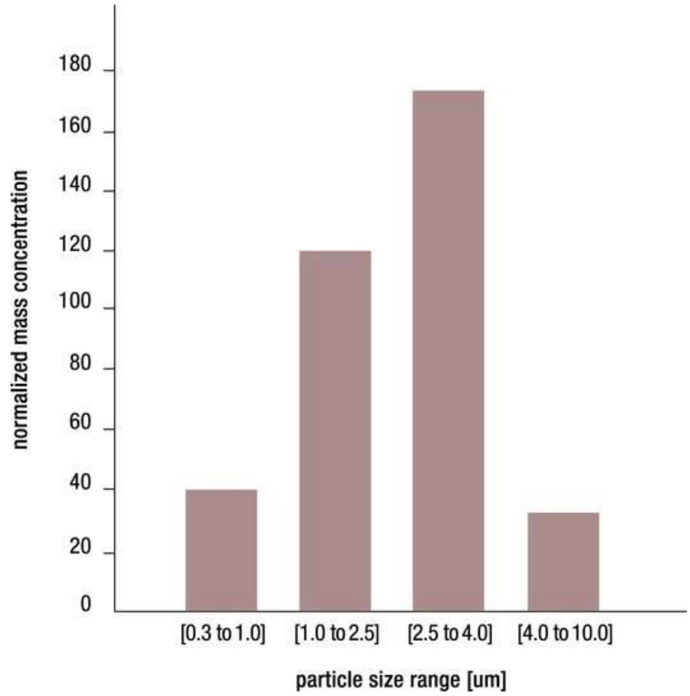

Fig.12 Particle composition of heavy dust (Source: Sensirion)

Dust Resistance

As mentioned previously a PM sensor is in principle very susceptible to output drift due to the accumulation of dust on the crucial optical parts of the device, namely the laser, the photodiode and the beam-dump (used to absorb the laser light and avoid parasitic scattering). Based on more than 20 years of experience in flow sensor design for several demanding markets and applications (e.g. automotive, medical, industrial and smart energy), Sensirion's engineers have developed and integrated an innovative and proprietary flow path technology in the SPS30 that prevents dust and dirt accumulating on the optical components. The result of a stress test, where a sensor is exposed to the equivalent of five years' dust exposure in Beijing, is shown in Fig. 6. The picture clearly shows that the flow path protects the crucial optical elements from dust exposure, and that the laser and photodiode are completely clean even after the stress test (the beam-dump, which is also protected from dust accumulation, is not visible in the photo).

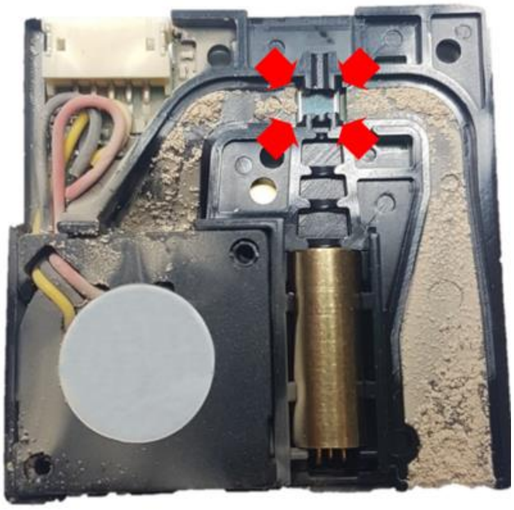

Fig.13. Clean photodiode after stress test (Source: Sensirion)

Summary

In summary, Sensirion's dust resistance and advanced binning technologies provide benefit to applications in several industries, including air quality monitoring, air purifiers and HVAC. A sensor that works over the whole lifetime of a device guarantees good air quality to the final user and increases energy efficiency and sustainable operation. Advanced binning and higher accuracy help to trigger specific actions based on the detected particle composition and improve the monitoring of filter lifetime based on the contaminant type information collected over the device's operation.

WATER QUALITY MESURMENT

Water is essential to life, as we know it. However, statistics reveal that, in year 2000, one billion people lacked access to safe drinking water and 2.4 billion to adequate sanitation. To achieve United Nations target of reducing by half the proportion of people without sustainable access to safe drinking water by 2015, an additional 1.5 billion people would require access to some form of improved water supply by 2015, that is an additional 100 million people each year (or 274,000/day) until 2015. Because water sources are limited, it is of paramount importance to keep its quality at the highest level possible. Threats to water are manifold, from industry to natural phenomena, and water quality assurance is a basic environmental issue involving from political to technical aspects and options, but it is obvious that no assessment of water quality is possible without a quantitative identification of some characteristics, a process commonly called water quality monitoring. This chapter is an overview on water quality and on its monitoring. The text reflects he experience of the authors on the subject, presents some research and development results they obtained in the last decade and includes data gathered from different sources, namely from USEPA reports and North Caroline State University Water Quality Group documents. The text includes remarks about measuring techniques for different water quality parameters that result from the experience acquired by the authors in the implementation of several water quality-measuring units. The last part of the chapter proposes architectures and intelligent signal processing techniques for distributed water quality monitoring networks.

Water quality

Water quality is commonly defined by its physical, chemical, biological and aesthetic (appearance and smell) characteristics. Water may be used for drinking, irrigating crops and watering stock, industrial processes, production of fish, shellfish and crustaceans, wildlife habitats, protection of aquatic ecosystems, navigation and shipping, recreation (swimming, boating), and scientific study and education.

Factors influencing water quality

Water quality is closely linked to the surrounding environment and land use. Liquid water is never pure and is affected by agriculture, urban, industrial and recreation uses. The modification of natural stream flows and the weather can also have a major impact on water quality. Groundwater is a major source of water and, when close to urban or industrial development, is vulnerable to contamination. Generally, water quality of rivers is best in the headwaters, where rainfall is often abundant, declining as rivers flow through regions where land use and water use are intense and pollution from intensive agriculture, large towns, industry and recreation areas increases. There are of course exceptions to the rule and water quality may improve downstream, behind dams and weirs, at points where tributaries or better quality groundwater enter the mainstream, and in wetlands. Rivers frequently act as conduits for pollutants by collecting and carrying wastewater from catchments and, ultimately, discharging it into the ocean. Storm water, which can also be rich in nutrients, organic matter and pollutants, finds its way into rivers and oceans mostly via the storm water drain network.

Water quality and ecosystems

An ecosystem is a community of organisms - plants, animals, fungi and bacteria - interacting with one another and with the environment in which they live. Protecting aquatic ecosystems is in many ways as important as maintaining water quality, for the following reasons:

•Aquatic ecosystems are an integral part of our environment. They need to be maintained if the environment is to continue to support people. World conservation strategies stress the importance of maintaining healthy ecosystems and genetic diversity.

•Aquatic ecosystems play an important role in maintaining water quality and are a valuable indicator of water quality and the suitability of the water for other uses.

•Aquatic ecosystems are valuable resources. Aquatic life is a major source of protein for humans. In most countries, like Portugal, commercial and sport fishing is economically important.

Water quality assessment

The presence of contaminants and the characteristics of water are used to indicate the quality of water. These water quality indicators can be categorized as:

Biological: algae, bacteria

Physical: temperature, turbidity and clarity, color, salinity, suspended solids, dissolved solids, sediment

Chemical: pH, dissolved oxygen, biological oxygen demand, nutrients (including nitrogen and phosphorus), organic and inorganic compounds (including toxicants)

Aesthetic: odors, taints, color, floating matter

Radioactive: alpha, beta and gamma radiation emitters.

Measurements of these indicators can be used to determine and monitor changes in water quality and to determine whether the quality of the water is suitable for the health of the natural environment and the uses for which the water is required. The design of water quality monitoring systems is a complex and specialized field. The range of indicators that can be measured is wide and other indicators may be adopted in the future. The cost of a monitoring system to assess them all would be prohibitive, so resources are usually directed towards assessing contaminants that are important for the local environment or for a specific use of the water. The paragraphs that follow detail several aspects of these quantities, algae, bacteria and radiations excluded. The paper includes a short reference to systems for on-line, in-situ water quality monitoring and ends with a list of references.

WATER QUALITY PARAMETERS AND MEASURING TECHNIQUES

Temperature

Temperature is an important water parameter because it is an influence quantity for the generality of other water parameters and also because it determines many physical characteristics of a water body. In the winter, water's temperature-dependent density allows aquatic life to survive. Ice is formed at 0 ºC and thus remains at the top of the water body. Sun shining through the ice will serve to warm the water below slightly, keeping the temperature just above freezing. Water at 4 ºC is the densest, and will sink to the bottom and be replaced by lighter 1 - 3.9 ºC water. The continual process of heating and sinking keeps the water body from freezing entirely [1]. In addition, temperate lakes stratify during the summer because of water's temperature-dependent density. Stratification prevents the mixing of oxygen and nutrients in the water body, and often encourages dissolved oxygen depletion. During the spring, stratification will break down allowing mixing of oxygen and nutrients. During the fall, the water body loses heat until its temperature is uniform at 4 ºC. Wind creates circulation, which distributes oxygen and nutrients throughout the water body (fall overturn). Eventually, the surface water layer falls below 4 ºC, becomes less dense, and remains at the surface. Ice will form if temperatures are low enough; otherwise, this upper layer will remain just above 0 ºC. Deeper water will remain roughly at 4 ºC until spring [11]. Higher temperatures often exacerbate low dissolved oxygen level problems in lakes and reservoirs. High temperatures encourage the microbial breakdown of organic matter, a process that requires dissolved oxygen. Unfortunately, warm water naturally holds less dissolved oxygen. Thus, persistent warm conditions may lead to a depletion of dissolved oxygen in the water body.

Measuring techniques

Temperature probes

Temperature range is usually from 0 to 30 ºC. Thus thermistor, platinum or even electronic based probes are adequate. Some manufacturers, like Quanta, commercializes probes that can measure several water parameters, including temperature (multi-parameter probes).

Turbidity

Turbidity is a quantity quantifying the degree to which light traveling through a water column is scattered by the suspended organic (including algae) and inorganic particles. Light scattering increases with the quantity of solids suspended in water. According to the research work developed by Campbell Scientific, usually the values of turbidity are correlated with the suspended solids concentration –SCC (Fig. 1); however, cases are also reported where no correlation between these two quantities is registered. Turbidity is commonly measured in Nephelometric Turbidity Units (NTU).

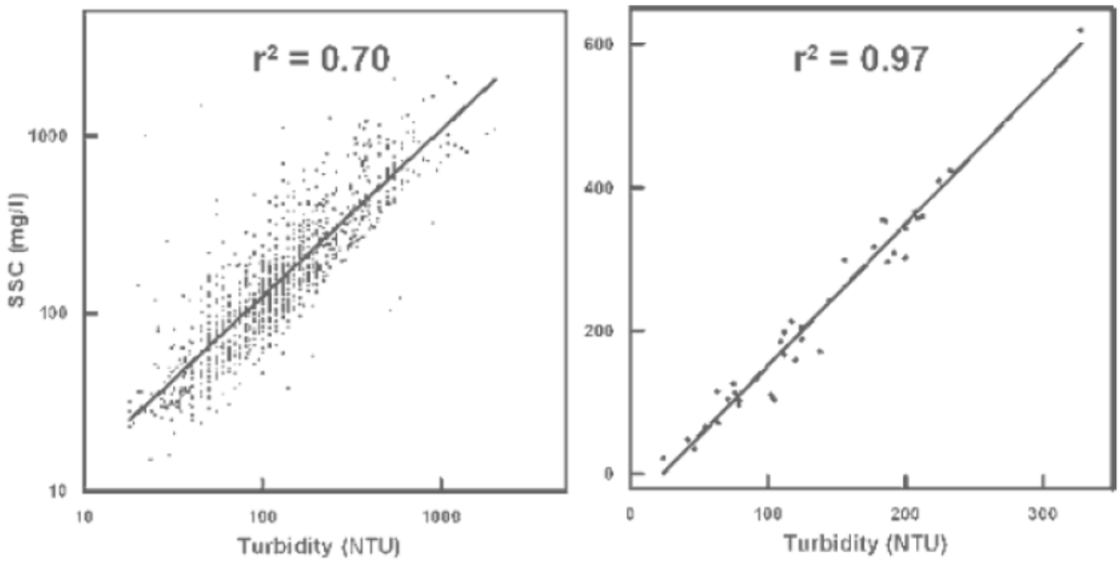

Fig.14 The graph on the left provides measurements of runoff from a freeway, which indicates a bad correlation between SSC and turbidity. The graph on the right provides measurements from San Francisco Bay that indicates a good correlation between SSC and turbidity (Campbell Scientific document)

The velocity of the water resource largely determines the composition of the suspended load. Suspended loads are carried in both the gentle currents of lentic (lake) waters and the fast currents of lotic (flowing) waters. Even in flowing waters, the suspended load usually consists of grains less than 0.5 mm in diameter (Table 1). Suspended loads in lentic waters usually consist of the smallest sediment fractions, such as silt and clay [2].

Sediment class Size (mm)	Size (mm)
Sand	
V. Coarse	1.5
Medium	0.375
V. Fine	0.094
Silt	
V. Coarse	0.047
Medium	0.0117 (not visible to the human eye)
Fine	0.0049
Clay	<0.00195

Table 1. Size classification of sediments (adapted from [12]).

Numerical categories

Designated Use	Acceptable Ranges
Recreation	5 NTU [4]
Aquatic Life	< 50 NTU instantaneously or < 25 NTU for a 10 day average [5] < 10 NTU for trout waters or < 25 NTU for streams (non-trout waters) or < 50 NTU for lakes and reservoirs (non-trout waters) [6]

Human Consumption 1 to 5 NTU (up to 5 NTU is allowed if the water supplier can demonstrate that this level does not interfere with:

1. Disinfection
2. Maintenance of a disinfecting agent
3. Microbiological determination [13]

Turbidity may be due to organic and/or inorganic constituents. Organic particulates may harbor microorganisms. Thus, turbid conditions may increase the possibility for waterborne disease. Inorganic constituents have no notable health effects. If turbidity is largely due to organic particles, dissolved oxygen depletion may occur in the water body. The excess nutrients available will encourage microbial breakdown, a process that requires dissolved oxygen. In addition, excess nutrients may result in algal growth. Although photosynthetic by day, algae respire at night, using valuable dissolved oxygen. Fish kills often result from extensive oxygen depletion.

Measuring techniques

Nephelometric Method: Comparison of the light scattered by the sample and the light scattered by a reference solution [9].

•Detection limits: Should be able to detect turbidity differences of 0.02 NTU with a range of 0 to 100 NTU.

•Interferences: Rapidly settling coarse debris, dirty glassware, presence of air bubbles, and surface vibrations. It is important to underline that turbidity is a measurement of the light scattering intensity relatively to the one that is obtained with the turbidity calibration standards. Visual clarity, measured as Secchi [10][11] or black disc visibility, is a direct measurement of the amount of suspended solids in water but its measurement requires more expensive equipment. Nevertheless, clarity measurements are more precise than turbidity measurements.

Salinity

The total dissolved solids (TDS) in water consist of inorganic salts and dissolved materials. In natural waters, salts are chemical compounds comprised of anions such as carbonates, chlorides, sulphates, and nitrates (primarily in ground water), and cations such as potassium (K), magnesium (Mg), calcium (Ca), and sodium (Na) [16]. In ambient conditions, these compounds are present in proportions that create a balanced solution. If there are additional inputs of dissolved solids to the system, the balance is altered and detrimental effects may be seen. Inputs include both natural and anthropogenic sources.

Total dissolved solids and conductivity

The presence in water of different anions and cations in different proportions leads to different values of water electric conductivity. However, even if it exists almost a linear relation between salinity and conductivity, that relation depends on the type of the dissolved salt. Moreover, conductivity is a non-selective measurement because instead of salinity, it gives the contribution of all charge carriers and not of a specific one. Notwithstanding, commonly, salinity is indirectly measured using conductivity meters. As an example, Fig. 15 represents the experiment results of the relation that is obtained between TDS and conductivity for a variable amount of NaCl dissolved in water. In this case, the correlation coefficient between both variables is almost equal to 1, meaning that the relation between both variables is practically linear.

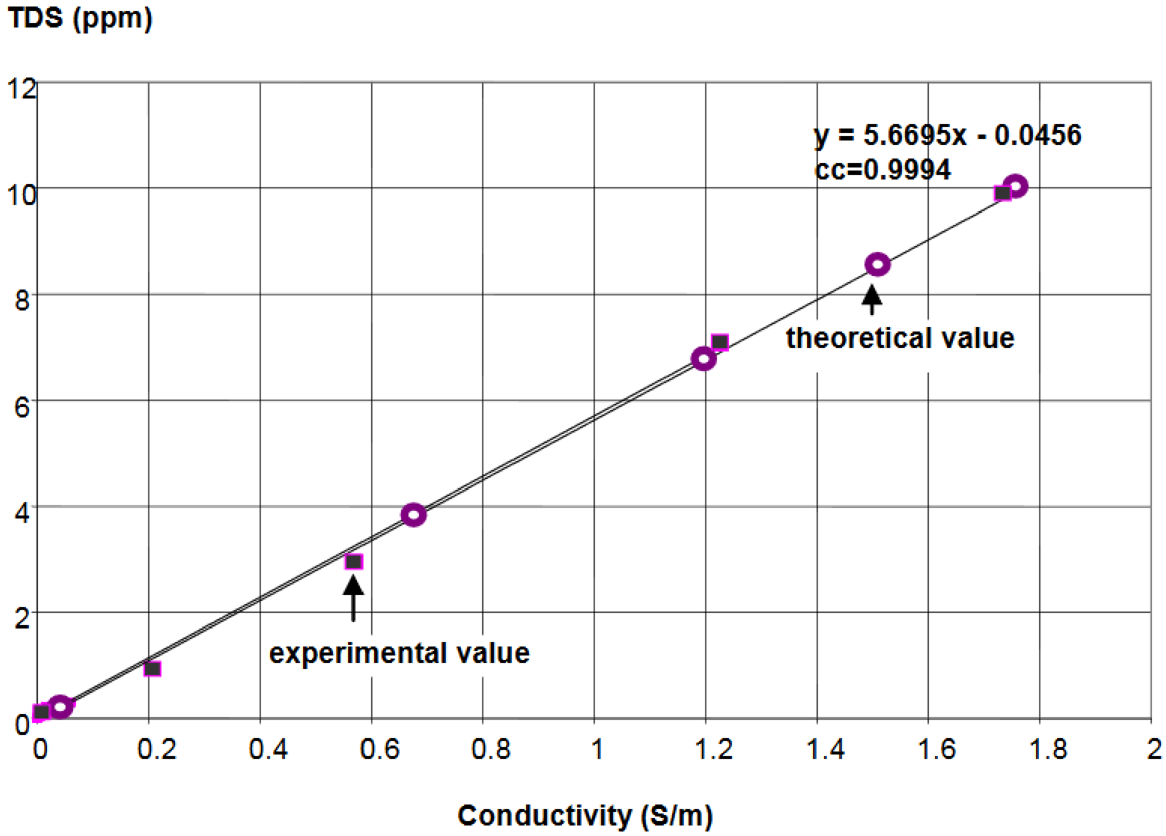

Fig.15 Experiment results of the relation that is obtained between TDS and conductivity for different values of NaCl dissolved in water (square symbol: experimental data; circle symbol: theoretical data).

It is important to underline that the equation of the straight line that is represented in the graph, namely its slope, depends mainly on the type of salt and on the ionic activity of the elements that are dissolved in the water and on the temperature of the solution.

pH

pH is defined as the negative log-base 10 of the hydrogen ion activity:

$$pH = - \log10 [aH+] \quad (1)$$

As long as the hydrogen ion concentration is not too high (less than 10-3 M), this activity is approximately proportional to the hydrogen ion concentration, more precisely:

$$[aH+]=\gamma\cdot[H+] \quad (2)$$

where γ represents the activity coefficient. This coefficient is always lower than one and is almost equal to one for low hydrogen ion concentration. The pH is a log-base 10 scale that measures acidity of a solution on a scale of 0 to 14. The pH of neutral solutions, such as pure water, is equal to 7. Alkaline solutions will have high pHs (8-14) and acidic solutions will have low pHs . Since the pH is a log-base-10 scale, the pH changes 1 unit for every power of ten changes in [H+]. For example, water with a pH of 3 has 100 times the amount of [H+] that is found in a pH 5 water. Because pH = - log10 [H+], the pH will decrease as the [H+] increases.

Numerical categories

Although near-neutral pH values are preferred, industry as a whole can tolerate a wide pH range, depending on the intended water use. The Environmental Protection Agency reports

Optimal pH Ranges	Designated Use
6.0 -8.5	General Agriculture [28]
6.8 - 8.5	Dairy Sanitation
4.5 - 9.0	Irrigation water [12]
5.0 - 9.0	Human Consumption [28]
6.5 - 9.0	Freshwater aquatic life
6.5 - 8.5	Marine aquatic life [12]
	Industry [28]
> 8.0	Boiler Feedwater
6.5 - 7.0	Brewery
6.5 - 7.5	Cooling Water
> 7.5	Cannery
6.0 - 6.8	Laundering
> 7.0	Oil Well Flooding
7.8 - 8.3	Rayon Manufacturing
6.8 - 7.0	Steel Manufacturing
6.8 - 8.0	Tanning

Table 2. pH ranges for different designated use.

A reduction in pH (more acidic) may allow the release of toxic metals that would otherwise be absorbed to sediment and essentially removed from the water system. Once mobilized, these metals are available for uptake by organisms. For many metals, the rate of uptake is directly proportional to the levels of metal availability in the environment. Thus, a decrease in pH increases metal availability, lending itself to greater metal uptake by organisms. Metal uptake can cause extreme physiological damage to aquatic life [17]. An increase in pH may cause heightened ammonia concentrations [16]. At low pH, ammonia combines with water (H2O) to produce an ammonium ion (NH4+) and a hydroxide ion (OH-). The ammonium ion is non-toxic and not of concern to organisms. Above a pH of 9, ammonia (un-ionized) is the predominant species [18]. The un-ionized ammonia (NH3) is very toxic to organisms. Thus, organisms experience ammonia toxicity more readily at higher pH [19]. Experiments have shown that a pH decrease of 1.4 units of pH can disturb the aquatic community.

Dissolved oxygen

Dissolved oxygen (DO) refers to the volume of oxygen that is contained in water. Oxygen enters the water by photosynthesis of aquatic biota and by the transfer of oxygen across the air-water interface. The amount of oxygen that can be held by the water depends on the water temperature, salinity, and pressure. Gas solubility increases with decreasing temperature (colder water holds more oxygen). Gas solubility increases with decreasing salinity (freshwater holds more oxygen than does saltwater). Both the partial pressure and the degree of saturation of oxygen will change with altitude. Finally, gas solubility decreases as pressure decreases. Thus, the amount of oxygen absorbed in water decreases as altitude increases because the atmospheric pressure decreases [11]. Microbes play a key role in the loss of oxygen from surface waters because they use oxygen as energy to break down long-chained organic molecules into simpler, more stable end-products such as carbon dioxide, water, phosphate and nitrate [12]. If high levels of organic matter are present in water, microbes may use all available oxygen.

Criteria to maintain designated use	
Designated Use	**Lowest acceptable DO levels (mg/l)***
Aquatic life	
Warm water fish	5.0
Cold water fish	6.0
Spawning season	7.0
Estuarine biota	5.0
Recreation	
Primary Contact	3.0
Secondary Contact	3.0
* Summary of state standards.	
Preferred ranges for designated use	
Designated Use	**Ranges (mg/l DO)**
Industry	
Boiler Feed Water	
High Pressure	0
Low Pressure	0.1 - 1.4

Table 3. Dissolved oxygen designated use and lowest acceptable levels.

RIVER MONITORING

Without water, no life could exist, and many essential and nonessential human activities wouldn't be possible without the use of healthy watersheds. These same activities can impact watersheds, in ways both large and small. Watersheds often span political and cultural boundaries; while neighbors separated by city, state or national borders may not live under the same legal and cultural guidelines as one another, both could be citizens of the same watershed. By this measure, ensuring the health of a watershed — or the lakes, streams and rivers within — is as much a responsibility to your fellow human as it is to your local, state or federal regulating agency. For this same reason, water quality regulations are increasingly focused on the watershed level rather than established by political boundaries.

Streams and rivers offer an above ground glimpse at the health and hydrology of a watershed, and function as a vital resource for human activity, as well as habitat for a host of non-human animals and plants. If a stream or river may be impacted by your project, it is vital to establish a proper monitoring system to ensure that the waterway's hydrology and water quality are affected as little as possible, and so that any impact can be mitigated if it is detected.

Typical River Monitoring System

There are many hydrological and water quality parameters that can be measured in a stream or river, but the needs of one monitoring project can differ widely from another. The number of monitoring sites, their locations, and the instruments used at each will vary from project to project, but a common solution is based around at least one stream gage site and related instruments.

To be effective, measurement data should be provided in real time. The easiest and most efficient way to do this is with a stream gage station installed on a riverbank or standing structure, such as a pier or bridge support. A stream gage built around a stilling well can contain other instruments, such as multi-parameter sondes equipped with an array of sensors, as well as data loggers and telemetry systems. With multiple telemetry options to choose from, continuous real-time data are available from any computer. This ensures that the project runs smoothly, and any control measures can be implemented immediately if parameter limits are exceeded.

Stilling Well

A stilling well is an isolated reservoir that permits inflow and outflow of river water, and is usually equipped with a submersible pressure transducer, bubbler, or shaft encoder to measure stream stage. Stilling wells can be installed in the riverbank or attached to standing structure, and may be housed along with a datalogger and telemetry system.

Integrated Data Logging System

An integrated data logging system is a real-time monitoring station that houses the data logger, telemetry module, and power/charging supply. Since it is generally cost-prohibitive to run AC power to the monitoring location, integrated solar panels are used to continuously charge the 12VDC battery for autonomous operation.

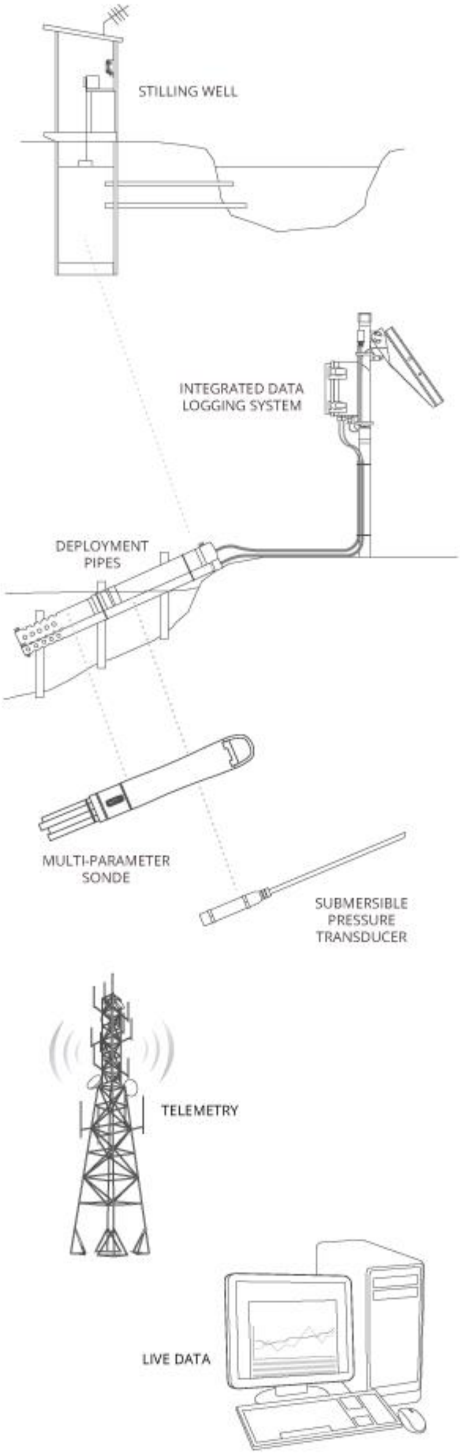

Fig.15 Different techniques for Remote River monitoring

Multi-Parameter Sonde

Multi-parameter sondes offer a versatile platform for deploying several sensors at a common site. These sondes can also act as an interface between sensors and a data logger or power source.

Submersible Pressure Transducer

A submersible pressure transducer measures the combined pressure exerted on it by the atmosphere and the head of water above it. A vent tube in the cable automatically corrects for atmospheric pressure influences.

Telemetry

Telemetry provides access to data in real time. The wireless communication can be radio-to-shore, cellular, or satellite based.

Live Data

Instant access to project data is available 24/7 through a cloud-based data center. Monitoring data can be viewed in real time, or as a graph to identify trends. Real-time automated alerts can be sent via text or email when specified parameters exceed predefined limits.

Monitoring Location

The monitoring objectives will determine the approximate location of the stream or river station. Site-specific characteristics must also be considered to ensure a successful project. Physical constraints of a site, the time required to reach the location, legal and physical access to a site and safety issues must be considered when making site selections.

Site Considerations

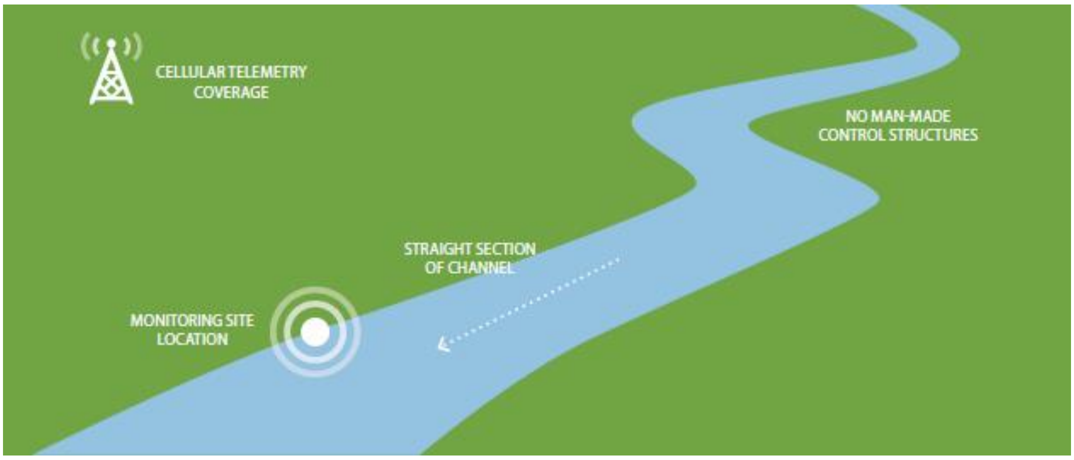

Fig.16 Site considerations for Remote River monitoring

- The monitoring location should be relatively accessible for carrying in equipment to perform periodic calibration and maintenance.
- If using telemetry, determine whether there is sufficient cellular coverage to get a signal from the site. If not, satellite telemetry will likely be required.
- The installation site should be selected so that flow conditions are reasonably constant over the physical area occupied by the beams.
- The sensor should be located in a straight section of the channel, away from curves that can cause variations in the flow distribution.
- Avoid man-made control/flow structures upstream or downstream of site that may change flow profiles erratically, as this will make rating development difficult.

Installation Considerations

- Make sure data logging and telemetry equipment will be installed sufficiently above the high water mark to prevent it from being flooded or otherwise damaged by high water.

- Install the sensors based on lowest expected stage. Also consider whether ice will form in winter months. If so, try to keep sensors installed below the freeze line.

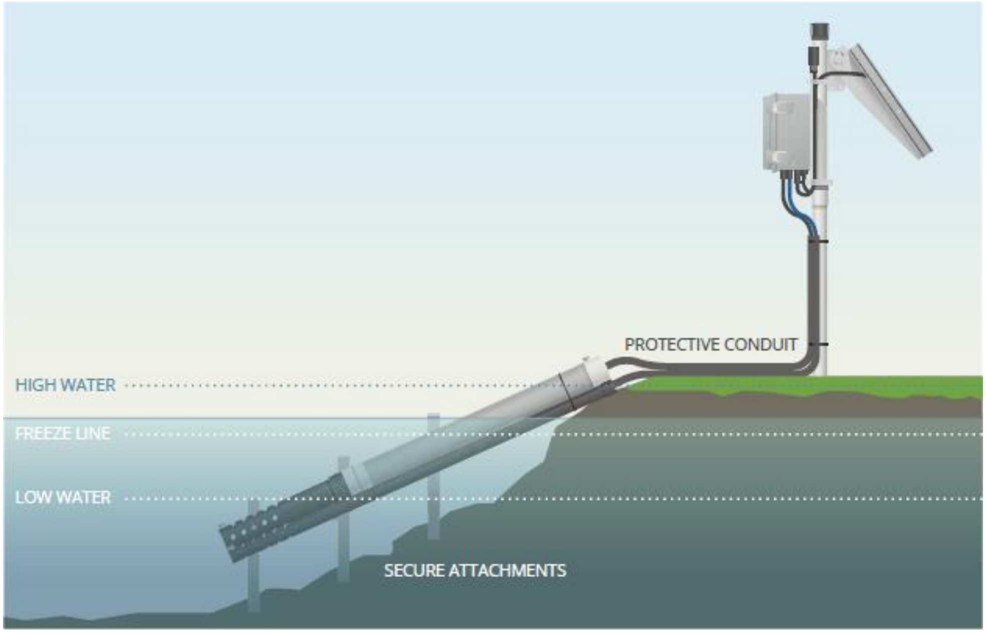

Fig.17 Installation considerations for Remote River monitoring

- Consider sediment issues and try a vertical stilling well whenever possible.
- Sensor mounting pipes should be securely attached to the stream or river bank with a bottom pin so that the sensor is always redeployed at the same location.
- Any potentially exposed sensor cables near the ground should be run through conduit to the data logger box to protect from animals.

Conclusion

Water quality monitoring is a complex issue because there are a large number of parameters that can be used to access its quality. Understanding the meaning of each parameter requires a good knowledge of different areas, namely electrical, electrochemical and biological engineering, among others. Measuring techniques is still an open field for some variables, particularly in which concerns in-situ and on-line measurement systems. As referred in the introduction, this chapter contains an initial overview related with water quality parameters based on the information available from different entities accredited in the field. However, some remarks about measuring techniques for different water quality parameters were introduced by the authors according to their experience in the field. The last part of the paper focus different water quality monitoring architectures that were used by the authors for distributed sensing and intelligent signal processing network for water quality monitoring.

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