Wireless Sensor Networks for Environmental Monitoring: A Review of Sensors, Communication Technologies, and Applications

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I. Introduction

The increasing urbanization and climate change have diverse impacts on different layers of society, threatening individuals in vulnerable situations during disasters such as floods, or affecting agricultural production due to climatic variations [29]–[32]. These phenomena highlight the need for effective monitoring systems that can provide more data on environmental conditions and help us monitor, analyze, and predict such events [31], [33]–[35].

When we talk about environmental monitoring, we refer to a wide range of applications and devices. Particularly in remote and hard-to-reach areas, this represents a significant technical challenge. The vastness of these territories, combined with adverse environmental conditions and the growing demand for real-time data, requires technological solutions that are robust, cost-effective, and scalable [36]–[38].

In this context, Wireless Sensor Networks (WSNs) have established themselves as a promising tool, offering significant advantages in terms of deployment flexibility, quick responsiveness, and cost-benefit compared to traditional monitoring infrastructures. WSNs enable dense spatial sampling and continuous data collection—critical aspects for tracking natural phenomena [10], [36], [38].

The need for real-time environmental monitoring has increased the demand for data, highlighting the importance of low-power, long-range technologies such as LoRa. These technologies are particularly suitable for applications in remote areas where communication infrastructure is limited or non-existent [10], [36], [38].

Additionally, we see a growing trend in the demand for data integration with artificial intelligence systems, which can extract valuable insights and trends and support real-time decision-making. This integration enhances the predictive capabilities of environmental monitoring systems and opens opportunities for new applications [10], [34], [36], [39], [40]. In 2021, a new definition was proposed for this concept, combining AI and IoT as AIoT, referring to the integration of artificial intelligence with the Internet of Things (IoT) to create smarter and more autonomous systems [40].

This literature review is structured into five main sections. First, it addresses the sensors and technologies used in environmental monitoring, categorizing them according to their application domains (hydrological, soil, and air quality). Next, the role of Wireless Sensor Networks and associated communication technologies is discussed. Then, the main challenges and current trends in the field of environmental monitoring are presented, focusing on technological innovations. Finally, conclusions and future perspectives are outlined.

Although previous reviews have thoroughly examined sensors for soil monitoring, such as those by [12], [41], [42], or water level measurement techniques as in [3], [4], [39], there is a notable lack of recent studies that comprehensively integrate both sensor technologies and communication infrastructures, bringing emerging concepts in environmental monitoring and going beyond specific applications.

This review aims to fill that gap by offering a broad perspective that covers sensor technologies applied to the monitoring of soil, water, and/or air/chemical compounds, along with an analysis of wireless communication technologies, energy efficiency strategies, and security challenges in WSN deployments for environmental monitoring. The main contribution of this work is to consolidate multidisciplinary advances, highlight underexplored technologies, and provide a comparative analysis to guide future research and applications in the development of environmental monitoring projects.

II. Sensors and Technologies for Environmental Monitoring

Our daily lives are full of sensors constantly collecting data about the environment around us. These sensors can be

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classified in many different ways. Some relevant categorization examples include: active and passive sensors, where active sensors emit some type of signal to measure a physical quantity, while passive sensors only capture signals that already exist in the environment [1]. Another way to classify sensors is by how they interact with the environment, where contact sensors measure physical quantities directly in contact with the medium, while non-contact sensors measure physical quantities without needing direct contact [1], [3], [4]. Finally, there are many other ways to classify sensors; in this work, we chose to group sensors according to the type of environment where they are applied, such as water level sensors, air quality sensors, and soil sensors, in order to better guide research in those environments.

III. Water Monitoring

When talking about water monitoring, we can divide the sensors into two main types: water level sensors and water quality sensors. Water level sensors are used to measure the height of the water column in water bodies like rivers, lakes, and reservoirs or in controlled environments like tanks and wells. Water quality sensors are used to measure parameters such as pH, turbidity, electrical conductivity (EC), and other chemical compounds present in the water.

A. Water Level Sensors

For monitoring water levels in natural environments like rivers and lakes, traditional contact sensors stand out, such as pressure sensors or limnigraphs, which measure the pressure exerted by the water column on the sensor. One such sensor was tested by [5], showing good readings and being insensitive to parameters like water turbidity. However, the same study highlights a weakness of this technology—its use in harsh environments. In flood conditions, for example, with high debris loads and strong currents, these sensors can be compromised. Additionally, contact sensors for monitoring in natural environments may involve float systems that detect the water height relative to a fixed point, or floating sensors that use a float connected to a cable or rope to measure water height. These sensors are simple and effective but can be affected by factors like floating debris, temperature variations, and corrosion [5], [7]–[9].

When selecting sensors for water level monitoring in controlled environments like tanks and wells—and where long-range sensing is not a concern—we do not need to worry as much about floating debris. In these cases, the previously mentioned sensors for rivers and lakes can be used, as well as other simpler methods such as resistive water level sensors, which measure electrical resistance between two electrodes submerged in water. These sensors are inexpensive and easy to install but may be affected by corrosion and mineral deposits [3], [5].

For this category—monitoring level in controlled environments—there are also emerging technologies with great potential. One example is passive water level sensors based on acoustic waves. The SAW sensor measures strain or pressure variations in the tank wall caused by water level changes, converting these variations into response signals, as developed by [26] and [27]. Another promising technology is optical fiber-based water level sensors, which rely on the hydrostatic principle of Archimedes and use the variation of light transmitted through an optical fiber and a floating element to measure the height of the water column. This principle is demonstrated in the developments by [28]. These sensors are highly accurate but are still complex to install and operate.

For non-contact monitoring applications, this review highlights three approaches: ultrasonic sensors, LiDAR sensors, and remote monitoring via satellite imagery.

Ultrasonic water level sensors emit sound waves and measure the time it takes for the waves to return to the sensor. These sensors are widely used due to their accuracy and ability to operate in environments with temperature and pressure variations [7], [21]. For example, the ultrasonic sensor model GY-Us42 was tested, showing that the average error of the device is less than 3% [7]. Another model, the HC-SR04, was also evaluated as a technically and economically viable option for water level monitoring [21], and is a good choice for education, citizen science, and research due to its low cost [22].

LiDAR sensors use optical waves to measure distances and speeds and are widely used in metrology, environmental monitoring, archaeology, and robotics [6], [23]. The measurement principle of LiDAR is based on the surface roughness of the reflective surface to generate non-specular reflection (i.e., scattering) of the emitted laser beam. The near-infrared (NIR) wavelength range is most commonly used for this purpose, typically between 900 and 1100 nm (270–330 THz), due to the low cost of lasers operating in this range and the lower energy density compared to visible light [6], [23]–[25]. Like ultrasonic sensors, LiDAR measurements are based on time of flight (TOF), with two main TOF methods: pulsed TOF and AMCW TOF. In pulsed TOF, an optical pulse is emitted, and the return time is measured. In AMCW TOF, a continuous amplitude-modulated wave is used, and the phase difference between transmitted and received signals is used to determine distance [6].

These sensors have been explored as a low-cost alternative for measuring water levels from bridges, with lab and field tests showing good accuracy (error around 0.1%), though subject to variations due to sensor temperature and water surface roughness [8]. LiDAR sensors installed on riverbanks for flood monitoring were also tested with good results—the study showed that suspended particles in the water positively affected reading accuracy and that the sensor could also be used to detect suspended particle concentration [20]. Another study compared the TF-mini LiDAR sensor with limnigraph pressure sensors, highlighting the benefits of LiDAR's non-contact measurement method over the contact-based limnigraph method and validating LiDAR as an excellent choice among fluid level measurement technologies [5].

Another method for monitoring water levels in open environments is remote monitoring using satellite data, as in the work by [18], which uses satellite images and data to estimate the levels of a watershed. Similarly, [19] uses this technique and compares satellite-based estimates with traditional measurements taken at various points along a river, with both studies presenting positive results for this approach.

B. Water Quality

The work by [10] presents a water quality monitoring project that uses pH, turbidity, and electrical conductivity (EC) sensors, integrating local and distributed data fusion techniques with machine learning resources to improve real-time pollutant detection.

IV. Soil Monitoring

Soil monitoring is an essential tool to optimize crop growth, improve production efficiency, and promote more sustainable agricultural practices. Soil sensors enable continuous measurement of physical and chemical parameters, such as moisture and nutrient concentrations, providing real-time data to support decision-making in the field. The demand for these technologies is growing, driven by population growth, the need to increase food production, and the pressure for more efficient and environmentally conscious agricultural practices. A representative example is the soil moisture sensor market, which generated around US$147.5 million in 2020, with expectations to reach US$360.9 million by 2027, reflecting global interest in digital agriculture technologies [12].

Historically, agricultural management recommendations were developed based on broad agroecological zones, as occurred during the Green Revolution, when the focus was solely on increasing productivity through synthetic fertilizers, without adequately considering local soil and water conditions or the associated environmental impacts. Much of this legacy still persists, with practices based on centralized procedures and generic empirical relationships between nutrients, fertilizer doses, and productivity. In this context, soil sensors emerge as a key tool to break away from this "top-down" model and enable a "bottom-up" approach, where management decisions are guided by actual data specific to each agricultural microenvironment, in both space and time [11].

A. SAW, RFID, and Nanotechnology

As we know, agriculture can span vast areas, and in such cases, WSNs and traditionally LoRaWAN are widely applicable since they allow remote coverage of these areas [13]. That said, other coverage alternatives for large areas have been explored beyond the more traditional LoRaWAN. The work by [13] presents a monitoring system consisting of RFID sensors embedded in the soil, a vehicle that moves through the monitored area collecting data, and a data processing center capable of covering large areas. Another study developed by [14] explores the use of drones in a similar way to collect data in remote areas.

The work by [15] presents the development of an innovative batteryless soil moisture sensor, using NFC technology with energy harvesting. The device is powered by the magnetic field generated by the NFC reader and performs measurements of temperature, relative humidity, and volumetric water content in the soil. An integrated microcontroller processes the collected data and transmits it to the NFC chip via I2C, storing the information in NDEF format for later reading. The study also compares different soil moisture measurement methods, selecting the one best suited to the energy limitations of the system. With a working principle similar to RFID, passive SAW-type sensors are also presented as alternatives for monitoring soil characteristics, as explored by [14]. An innovative form of soil moisture detection was also explored by the same author using optical fibers installed over large areas to detect water concentration in the soil.

V. Air and Chemical Composition Monitoring

When thinking of urban environments integrated with IoT under the concept of smart cities, one of the most relevant parameters is air quality, due to its direct impacts on public health, the environment, and the global economy. Atmospheric pollution in urban areas, with non-uniform spatial and temporal distribution, reinforces the need for monitoring systems with high spatiotemporal resolution—something traditional monitoring systems still struggle to provide at scale and with broad data coverage [2].

In this context, the advancement of sensor technologies, such as MEMS and wireless sensor networks (WSNs), has driven the development of the concept of the Next Generation Air Pollution Monitoring System (TNGAPMS). For this type of application, the most concerning gases are carbon monoxide (CO), nitrogen dioxide (NO_2), ground-level ozone (O_3), and sulfur dioxide (SO_2). Currently, the most used and suitable sensors for monitoring these gases in urban and industrial settings are electrochemical sensors and solid-state (semiconductor) sensors, although there are also other low-cost technologies such as catalytic sensors, NDIR, and PID sensors, which are widely applied in various gas detection contexts [2].

A. Chemical Element Detection

The study by [16] investigates SAW sensors for passive detection of gases and chemical vapors in the air, based on the interaction of the compounds with the antenna, which alters the received acoustic signal. SAW sensors are shown to be viable for detecting inorganic gases such as NH_3, NO_2, SO_2, CO, organic vapors such as toluene, ethanol, acetone, and even chemical warfare agents. The study highlights the importance of material stability in extreme environments, the use of antennas for wireless operation, and low energy consumption, pointing to future research directions in sensitive materials, flexible sensors, and multi-element arrays for simultaneous gas monitoring.

B. Air Pollution and Quality

The work by [17] analyzes the performance of low-cost sensors (LCS) for monitoring various air pollutants, including carbon monoxide (CO), nitrogen oxides (NO and NO_2), ozone (O_3), and particulate matter ($PM_{2.5}$). The review highlights the potential of these sensors to expand spatial coverage in both urban and remote areas and assesses different calibration methods such as MLR, ANN, SVR, and RF, considering factors like relative humidity, which significantly affects particulate measurement.

The study by [2] presents a review of air pollution monitoring systems based on wireless sensor networks (WSNs), classifying them into three main categories: Static Sensor Networks (SSN), Community Sensor Networks (CSN), and Vehicular Sensor Networks (VSN), based on the types of sensor carriers. The analysis shows that many current solutions are already viable in terms of spatiotemporal resolution, cost, energy efficiency, ease of deployment, maintenance, and public data accessibility. However, challenges remain, such as the lack of 3D data acquisition, limitations in active monitoring capability, and the use of uncontrolled or semi-controlled carriers—factors that should be improved in the next generations of air pollution monitoring systems.

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The preferred spelling of the word "acknowledgment" in America is without an "e" after the "g". Avoid the stilted expression "one of us (R. B. G.) thanks . . .". Instead, try "R. B. G. thanks. . .". Put sponsor acknowledgments in the unnumbered footnote on the first page.

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