1-1-2020

Internet of Things in Water Management and Treatment

Abdul Salam
Purdue University, salama@purdue.edu

Salam, Abdul, "Internet of Things in Water Management and Treatment" (2020). *Faculty Publications.* Paper 31.
https://docs.lib.purdue.edu/cit_articles/31

https://doi.org/10.1007/978-3-030-35291-2_9

Chapter 9

Internet of Things in Water Management and Treatment

Abstract The goal of the water security IoT chapter is to present a comprehensive and integrated IoT based approach to environmental quality and monitoring by generating new knowledge and innovative approaches that focus on sustainable resource management. Mainly, this chapter focuses on IoT applications in wastewater and stormwater, and the human and environmental consequences of water contaminants and their treatment. The IoT applications using sensors for sewer and stormwater monitoring across networked landscapes, water quality assessment, treatment, and sustainable management are introduced. The studies of rate limitations in biophysical and geochemical processes that support the ecosystem services related to water quality are presented. The applications of IoT solutions based on these discoveries are also discussed.

9.1 Introduction

The survival of humanity depends on the availability of the water resources. The water stress is a major issue due to decreasing freshwater reserves in different regions of the world [2, 20, 23, 53, 89]. The issues of water shortage have exacerbated due to the climate change related variations in frequency and quantity of precipitation [5, 41, 98, 99]. Moreover, the growth in population and emerging human mobility patterns have also contributed to the worsening the issue of shortage. Therefore, the sustainable water resource management and treatment is vital to maintain and conserve the water supply to meet current growth needs and future generations [24]. The water amount and quality interactions impact the water security [33]. The water security is defined as [14, 38, 42]:

> The capacity of a population to safeguard sustainable access to adequate quantities of and acceptable quality water for sustaining livelihoods, human well-being, and socioeconomic development, for ensuring protection against

(continued)

> water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability.

In this chapter, the IoT applications using sensors for waste and stormwater monitoring across networked landscapes in water treatment and sustainable management are presented. The impacts of the human activities on amount and quality of the water are discussed in the next section.

9.1.1 Impacts of the Human Activities on Amount and Quality of Water

The human activities affect the water quantity and quality in different ways [111]. These activities span in various disciplines such as agriculture and forests. The human-induced impacts are discussed below:

- The irrigation water and drinking water withdrawals reduce the stream base flow and surface water table [26]. Accordingly, water temperature, oxygen concentrations are impacted, which lead to rise in summer water temperature, and nutrients concentrations whereby decreasing oxygen concentration.
- Similarly, in agriculture, the tile drainage results in disruptions to natural hydrology by increasing flow and flooding [101]. Accordingly, the wetland water and discharge levels are impacted that lead to increase in nutrients, pesticides, sediments, and reduce soil infiltration and nutrient cycling.
- The impervious surfaces in urban and industrial areas are another factor that impacts the quality and quantity of water. These surfaces are generally covered with impenetrable asphalt or concrete materials. These also cause disruptions natural hydrology and causation of increasing peak flow and flooding [62]. Accordingly, the turbidity and nutrients are impacted which result in an increase in sediments and contaminants which reduce nutrient cycling.
- In forests, the harvesting is done due to many different reasons that increase peak flow and disrupt natural hydrology [63]. The water turbidity, algae, and temperature are impacted. The forest harvesting practice leads to an increase in sediments, nutrients, and pesticides.

Therefore to ensure water security, there is a need for efficient management practices for water sustainability (Fig. 9.1). These water management practices are discussed in the following:

- Source Management. As discussed above, the watershed deterioration, due to agriculture and other land-use practices, accelerates the nutrients and sediments runoff process, which subsequently requires extensive treatment at the receiving end for cleanup operation [19, 102]. In source management, the water supplies

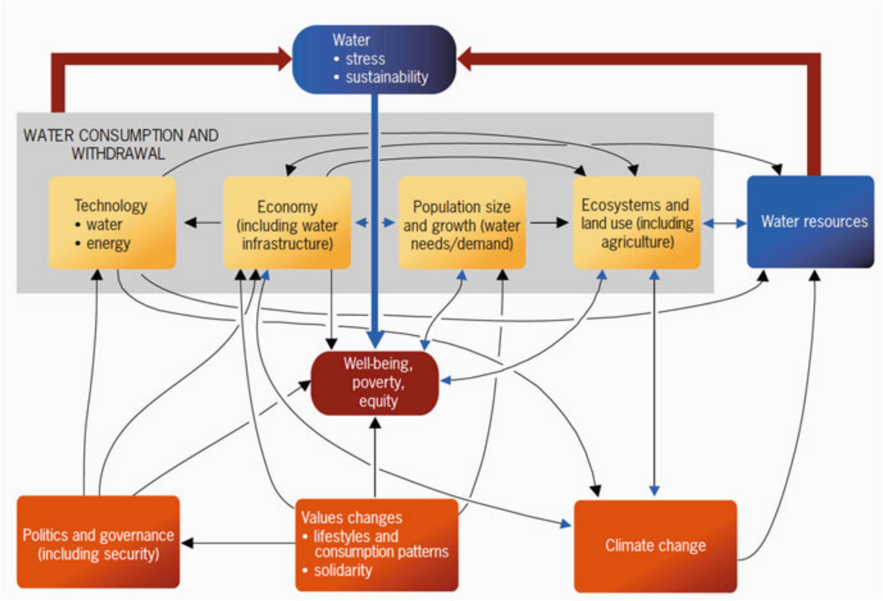


Fig. 9.1 The key factors in water security [34]

are protected at the source, however, the source tracking is a complex and challenging task. Water systems consist of different horological elements in wide geographical areas.

- The purpose-fit management. In this approach the treatment is done based on the end user needs [25].
- Other management practices include conservation, treatment, and reuse, which are discussed in detail later in the chapter.

9.2 Water Management and Treatment using IoT

The water management and treatment using IoT has the potential to overcome these key challenges for sustainable water management [51, 67, 68]. Through its sensing and communication technologies, it can provide useful insights into the sustainable water management approaches by using real-time data and decision support systems for better management and policy decisions. Novel technologies can be developed and connected to the system for water cycle and resource forecasting and understanding the connection between water quantity and land use. The adoption of modern sensing technologies can meet need of water use, quality, quantity sensing, and treatment. Accordingly, the inventory and indicators of the baseline conditions can be developed. It also enables efficient management of water stresses, pollutants, water data, land use, nutrients, and overflows using wireless communications and remote sensing.

The water management IoT's large scale monitoring of the chemical, physical, and biological properties in different types for water mediums (e.g., groundwater and mine-impacted water) has tremendous potential to inform better treatment options [103]. It is useful for large-scale water contaminant data collection and provides useful insights into the impacts of the contaminant. Accordingly, analytical models can be developed to set limits on contaminant. Moreover, based on the real-time sensing capabilities of the water management using IoT, the health alerts can be issued by the authorities. New techniques for toxin identification and quantification can be integrated into system for performance analysis. Accordingly, the treatment of large areas with high contaminant concentration becomes possible.

Furthermore, the movement of contaminant from watersheds to other water bodies such as rivers, estuaries, and other coastal zones. Moreover, real-time monitoring systems can be developed for in-water HAB [13, 36, 56] observations (such as environmental conditions conducive to HAB) that will aid in rapid species identification and timely mitigation actions. Accordingly, the large-scale empirical studies enabled by the Internet of Things paradigm can inform about the efficiency of different treatment techniques and vulnerable factors. This knowledge is useful to develop new tracking role of different sources (such as wild, human, and animal sources) for microbial contamination. Based on this approach, the combined water organisms can be studied.

It has the potential to establish urban underground infrastructure monitoring stormwater and wastewater overflow monitoring capabilities through integration of subsurface sensing and wireless underground communications [80]. This enables community managers to take timely management actions to control rising water levels which not only cause damage to infrastructure but also lead to community inconvenience. The water management using IoT is also an innovation driver for different sensing technology integration into real-time decision-making, such as in situ sensors, satellite based sensing, and LiDAR, and other in-water sensing methods. Through development of novel sensing techniques, it has also benefits to monitor the post-treatment quality of the water to ensure its safety for human consumption [11, 58, 66, 110].

9.2.1 Water Management and Treatment using IoT

The things in water management and treatment are presented in this section.

- Stormwater, wastewater, gray water, flooding, overflow
- Percolation, precipitation, runoff, flow regimes
- Sediments, nutrients, pesticides
- Water temperature, dissolved oxygen, and turbidity
- Treatment, recycling

9.3 Groundwater Sensing and Treatment

The groundwater is saturated into the pores underground. The groundwater remediation process includes converting the water pollutants into safe content for drinking or altogether eliminating them. Different techniques are used for groundwater treatment such as biological, chemical, and physical treatment methods. These are listed below [57, 60]:

- Excavation/removal
- Pump and treat
- Capping
- Soil vapor extraction (SVE)
- Multi-phase extraction systems (MPE)
- In situ bioremediation
- Air sparging
- Monitored natural attenuation (MNA)
- Vertical engineered barriers (VEB)
- In situ chemical reduction (ISCR)
- In situ thermal treatment

9.3.1 Applications of Nanotechnology in Groundwater Treatment

The nanotechnology is also being applied for remediation of groundwater [29, 97]. In Fig. 9.2, three different approaches of groundwater remediation based on iron particles applications are shown. In this approach, the contaminants in groundwater and dense non-aqueous phase liquid (DNAPL) interacts (physical contact or on being dissolved) with the iron particles for treatment. In Fig. 9.2a, a standard porous reactant barrier fabricated with high quality grainy Fe of the millimeter size is shown. In Fig. 9.2b, an area for reactive treatment is established by serial inoculation of nano-sized iron to develop converging areas of particles for adsorption in the grists of underground water. In Fig. 9.2c, the DNAPL contamination treatment approach by inserting movable nano-size particles is shown. In both Fig. 9.2b and c, the nano-size particles are shown in black, whereas the impacted zones are shown in pink color plumes. Moreover, in Fig. 9.2b there is no particle mobility, and in Fig. 9.2c, the particles are mobile.

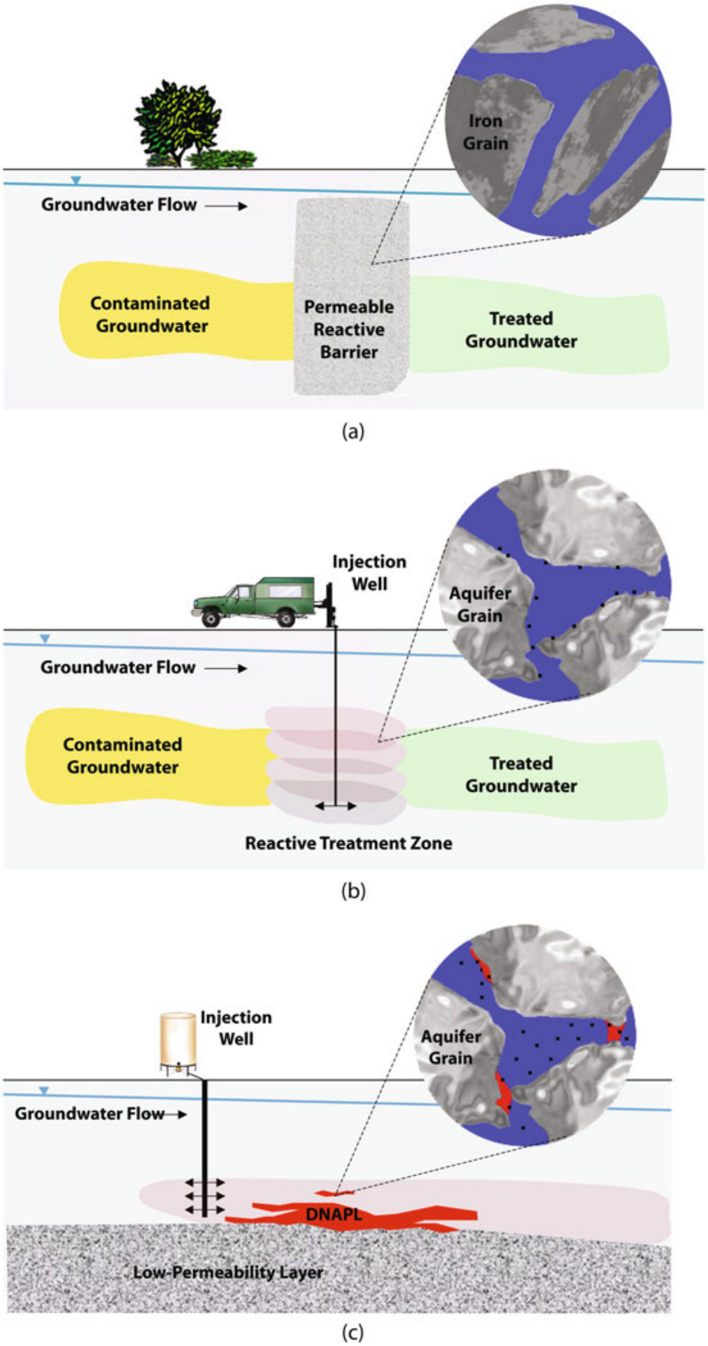


Fig. 9.2 Three approaches to application of Fe particles for groundwater remediation: (**a**) an area for reactive treatment is established by serial inoculation of nano-size iron to develop converging areas of particles for adsorption in the grists of underground water, (**b**) a 'reactive treatment zone' formed by sequential injection of nanosized Fe to form overlapping zones of particles adsorbed to the grains of native aquifer material, and (**c**) DNAPL contamination treatment approach by inserting movable nano-size particles [97]

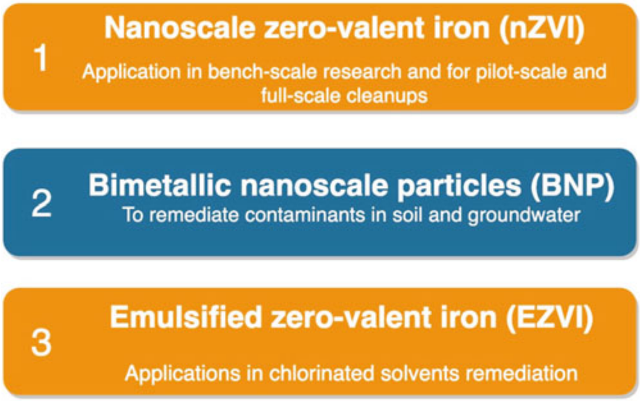


Fig. 9.3 Types of nanomaterials with their contaminant remediation capabilities

9.3.2 The Nanomaterials for Contaminant Remediation

Several types of nanomaterials have been used for the remediation of contaminants such as chloroethene, trichloroethylene (TCE), Tetrachloroethylene, and 1,2-dichloroethane (DCA). Various types of nanomaterials with their remediation capabilities are shown in Fig. 9.3. The nZVI are utilized in water treatment due to their elevated surface reactivity [52]. The iron particles (BNPs) are employed in groundwater by using the oxidation reduction reaction process in order to attain contaminant degradation. The EZVI are used to treat human carcinogen chlorinated hydrocarbons.

9.3.3 Hazardous Water Sensing and Treatment

The technologies for hazardous waste cleanup are discussed in the following. These contaminant can be found in different medias such as surface water, soil gas, soil, sediment, light non-aqueous phase liquid (LNAPL), groundwater, fractured bedrock, and dense non-aqueous phase liquid (DNAPL) [31].

- Phytotechnology. In this water and soil treatment technology, different types of plants are used to debase, remove, restrain, and disable contaminants [31].
- In situ chemical oxidation. In this approach, various oxidants are inserted in the underground environment to transform the contaminant into immobile components such CO_2 and CI−. This technology is very effective in treatment of non-aqueous phase liquids (NAPL) [31, 100].
- In situ flushing. In this soil and groundwater treatment technique, the flushing solutions (e.g., cyclodextrin, cosolvents, surfactants, oxidants, and chelants) are

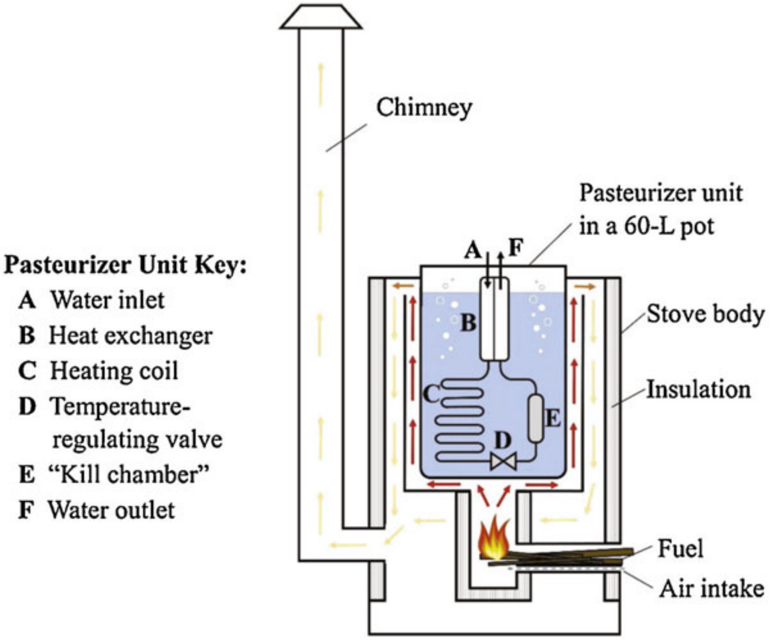


Fig. 9.4 A self-regulating biomass-powered system designed to heat water to the pasteurization temperature [22]

injected into the contamination areas to make contaminants either mobile or soluble. Accordingly, the mixed solution is treated either in situ or through extraction. The contaminants receptive to this type of treatment includes polychlorinated biphenyls (PCB), NAPLs, volatile organic compounds (VOC) and semi-VOCs, cyanides, pesticides, dioxins, metals, corrosives, and radioactive components [65].

- Heating Technologies. These are based on contaminants treatment by heating of water and underground environment using different heating techniques (e.g., conductive, electrical resistive, RF, steam, and hot air injection). These are used in PCB, polychlorinated, oil contaminants, and chlorinated solvents [47, 112] (Fig. 9.4).

9.4 Underground Communications in Urban Underground Infrastructure Monitoring

In this section, the path loss analysis of wireless underground communications in urban underground IoT for wastewater monitoring has been presented. The potential of wireless underground technology and sensor solutions in different transformative urban underground IoT applications (e.g., real-time flow monitoring, intrusion and infiltration (I&I) isolation, and smart manhole lids) is explored. The path loss model evaluations are done in different communication media under different layers thickness levels. The design of sewer and stormwater overflow monitoring systems can benefit from these findings.

9.4.1 Wastewater and Stormwater Monitoring Needs

Urban areas have public infrastructure worth billions of dollars located underground. City governments spend significant budget annually to support this underground infrastructure. The underground IoT solutions are rare due to challenges in connectivity and needs for extensive cabling to leverage over-the-air communication solutions, which increases costs. By combining wireless underground technology and sensor solutions [50, 106], many transformative urban underground IoT application such as real-time flow monitoring, intrusion and infiltration (I&I) isolation, and smart manhole lids can be developed.

The city wastewater bodies are responsible for collecting and treating wastewater at wastewater recovery facilities by processing many million gallons a day [49]. Cities have a strong need to monitor the quantity and quality of wastewater entering the collection system and reaching these recovery facilities [8, 10, 15, 28, 88]. Extra quantities of water entering the pipes can cause backups that result in sanitary sewer overflows [35, 59]. Eliminating I&I is important for controlling the flow of extraneous water into the pipeline [35, 95]. However, currently most cities do not have access to affordable underground sensor and connectivity technologies designed to detect problems in time to take preventive action. In this paper, we present the path loss analysis of wireless underground communications using urban underground IoT for wastewater monitoring [46, 90]. The architecture of urban underground IoT for wastewater monitoring is shown in Fig. 9.5. It shows different component of the system (e.g., base station, catch basin, UG transmitter and receiver, and drainage system). A storm drain is a major component of the drainage system and served as inlet and outlet for the runoff. Accordingly, it discharges the runoff to a water body (river, stream, channel, or creek).

The wastewater flow monitoring application can utilize wireless underground communication technology [104], which allows IoT radios to be buried underground [30]. Underground pipe monitoring sensors, connected to wireless underground software defined radios, can wirelessly connect to the roadside urban infrastructure at the nearest traffic light pole. This wireless underground technology has been shown to be successful in agricultural fields for several years with effective communication ranges of 100–200 m [106]. We present a theoretical path loss analysis for wireless underground communication through asphalt to design long-range wireless communication radios, which will allow underground radios to be deployed sufficiently deep to keep cabling to the underground pipes at a minimum while maintaining connectivity [9, 81, 86]. Providing this information to mobile

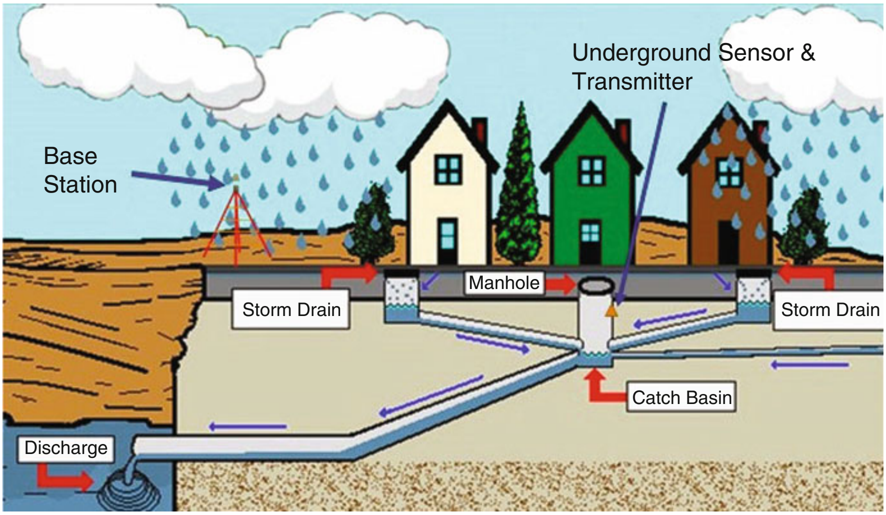


Fig. 9.5 The architecture of urban underground IoT for wastewater monitoring [80]

devices will enable large-scale dissemination of timely alerts during emergencies. This application can also drive realistic wireless traffic for evaluating solutions for wireless underground networks.

9.4.2 Internet of Underground Things for Wastewater and Stormwater Monitoring

Internet of Underground Things (IOUT) has numerous applications in the field of digital agriculture [3, 18, 30, 39, 54, 70–79, 81–85, 87, 94, 96]. Another important application is in the area of border monitoring, where this technology is being employed for border enforcement and to curtail infiltration [4, 93]. Moreover, IOUT is also being utilized for landslide and pipeline monitoring [39, 91, 92].

The IOUT delivers consistent access to data garnered from the farming areas via underground networking, aboveground networks, and the Internet. IOUT incorporates in situ underground sensing [1] of soil physical, chemical, and biological factors which includes water content sensing, salinity sensing, pH and nitrogen sensing, and temperature sensing. It also has the communication capabilities built-in as one of the integral component to provide the sensing data from the plants, roots, and soil. Moreover, it has the ability to include the environmental sensing capability to provide the real-time data pertaining to the diverse environmental phenomena such as wind data, rain information, and solar potential [107]. When integrated with agricultural machinery and farm equipment on the field (e.g., seeding equipment, irrigation controllers, harvesting machines and combines), the IOUT leads to the full self-sufficiency on the smart farming fields, and has the strong potential of development of enhanced food production solutions and applications in the area of digital agriculture [106]. The IOUT is also being utilized to provide useful decision-making information to the growers in the field in real-time.

In Sect. 9.4.4, the model evaluations are performed using different parameters.

9.4.3 Path Loss Model for Stratified Media to Air Communications

In this section we present the attenuation in the stratified medium and dispersion of subgrade of soil.

9.4.3.1 Attenuation in the Stratified Medium

The layered structure of the underground medium is shown in Fig. 9.2. The distinctive properties of wave transmission in the stratified medium need expressions of the path loss by taking into account the characteristics of different layers involved in the wireless communications [108].

Free Space Path Loss

From Friis equation [37], the received transmission power in over the air medium (OTA) at the transmitter-receiver (TR) communication path r from the transmitting antenna can be expressed by using the logarithmic scale as:

$$P_r = P_t + G_r + G_t - L_{fs}, \tag{9.1}$$

where the transmission power of the transmitter is P_t, the antenna gains of the transmitting and receiving antennas are expressed as G_r and G_t, and L_{fs} is over the-air-path as exhibited in the free space (expressed in dB), and it is written as:

$$L_{fs} = 33.2 + 20\log(d) + 20\log(f), \tag{9.2}$$

where the length of total transmission path (e.g., the distance between the transmission and the receiver antenna expressed in meters) is denoted by d; and the frequency of the operation of the communication system is expressed as f with unit in MHz.

We consider transmission loss at two levels: (1) free space path loss, (2) loss through stratified layers.

Propagation Loss in the Layered Medium

For the propagation through layered medium, loss through medium should account for the effect of the properties of different layers involved in communication. Accordingly, the strength of the signal received at the receiver can be rewritten as [105]:

$$P_r = -L_m + G_r + P_t + G_t, \tag{9.3}$$

where $L_m = L_{fs} + L_l$, and L_l denotes the extra signal attenuation exhibited by the transmission of EM waves through the stratified medium, which is ascertained by taking into account the existing dissimilarities of EM wave propagation occurring in the layered medium in comparison to that of the free space. The extra prorogation wave loss, L_l, in the stratified medium, hence, consists of accumulative loss occurring in total number of layered medium through which wireless communications is carried out:

$$L_l = \sum_{n=0}^{N-1} L_n, \tag{9.4}$$

where L_n is the attenuation loss in the nth layer for each of the N layers.

The transmission loss exhibited in a particular layer denoted as L_n, is mainly dependent on the di-electric permittivity, and the wavenumber of the medium in that particular layer, that can be expressed as $j\beta + \alpha = \gamma$ given as:

$$\alpha = \omega \sqrt{\frac{\mu\epsilon'}{2}\left[\sqrt{1 + (\frac{\epsilon''}{\epsilon'})^2} - 1\right]}, \tag{9.5}$$

$$\beta = \omega \sqrt{\frac{\mu\epsilon'}{2}\left[\sqrt{1 + (\frac{\epsilon''}{\epsilon'})^2} + 1\right]}, \tag{9.6}$$

where the ω, which is equivalent to the $2\pi f$, denotes the angulated spectrum of the frequency, the magnetized permeableness is expressed as the μ, the imaginary and real components of the permittivity of the material are denoted as ϵ'' and ϵ', respectively, (9.9). Consequently, the propagation loss, L_n, for a particular layer in the stratified medium is found as [48]:

$$L_n[dB] = 20 \cdot \gamma \cdot d \cdot \log 10(e), \tag{9.7}$$

where $e = 2.71828$, and d is thickness of the nth layer.

It can be seen that the propagation loss depends on the complex dielectric permittivity of the electromagnetic wave propagation in medium, layer thickness d, operating frequency, f, and other properties of the medium. Next, we consider the dispersion of next layer involved in the sewer overflow monitoring system.

9.4.3.2 Dispersion in Different Subsurface Layers

The ability of the materials in different subsurface layers to holdout against the applied electric charge defines its permittivity. The permittivity also depends on the electromagnetic absorption potential of the material. With the oscillation electric field, the charge flows and results in two charge components of the current (e.g., charging and loss). The heat loss represents the dissipated energy into the thermal excitation. The polarization of the soil and asphalt material in the subsurface layers is coupled with the dielectric properties and can be divided into dipolar, atomic, and electric types. It also depends on the frequency because the dielectric displacement and polarization response are different at different carriers. In the following, we discuss dispersion of materials involved in the subsurface layers. The material permittivity prediction expressions are presented.

9.4.3.3 Dispersion of Subgrade of the Soil Medium

By employing the findings of an extensive empirical campaign on soil permittivity [61], the permittivity spectra of the medium in the frequency range of 300 to 1300 MHz can be determined as shown in the following:

$$\epsilon_s = -j\epsilon_s'' + \epsilon_s', \tag{9.8}$$

$$\begin{aligned} \epsilon_s' &= 1.15\left[1 + \frac{\rho_b}{\rho_s}\left(\epsilon_s^{\alpha'}\right) + m_v^{\beta'}\epsilon_{f_w}'^{\alpha'} - m_v\right]^{1/\alpha'} \\ &-0.69, \quad \epsilon_s'' = \left[m_v^{\beta''}\epsilon_{f_w}''^{\alpha'}\right]^{1/\alpha'}, \end{aligned} \tag{9.9}$$

where the relative complex dielectric permittivity of the soil medium is denoted by ϵ_s, the m_v is used to express the measure of the volumetric water content present in the medium, the bulk density is ρ_b that is the indicator of the compaction of the soil material with unit of g/cm^3 and is used in relation to the solid soil particles ρ_s which is 2.65 g/cm^3. The value of the α' is 0.65. The value of other soil dependent experimentally determined constants β'' and β' is given as:

$$-0.52S + 1.28 - 0.16C = \beta', \tag{9.10}$$

$$-0.61S + 1.34 - 0.17C = \beta'', \tag{9.11}$$

where the amount of sand particles present in the soil is denoted by S, and contents of the clay particles found in soil is expressed as C. The relative dielectric permittivity of the free water (both the imaginary and real components) are represented by $\epsilon' f_w$ and $\epsilon'' f_w$.

9.4.3.4 Dispersion of Asphalt

Since, the medium of communications in sewer overflow monitoring application is multi-layer structure, hence, it is important to determine the dielectric value of asphalt layer (top surface in Fig. 9.6). The formula is given as:

$$\epsilon' = \frac{3}{4\pi}\frac{\epsilon_0 - 1}{\epsilon_0 + 2}. \tag{9.12}$$

Fig. 9.6 The layered structure of the underground medium [80]

It should be noted that when the frequency is increased the value of dielectric constant of asphalt also increases. The impact of dependency of the dielectric constant on the frequency is caused by dipolar polarization (e.g., the disassociation molecule charges). The asphalt substance (bitumen) contains many aromatic and asphaltene molecules. Accordingly, it also depends on the applied electric field.

9.4.3.5 Dispersion of Base Gravel Aggregate

The base gravel aggregate layers are comprised of different materials such as of stones, sand, pebble, and air voids in less organized fashion. Because of this semi-random organization, the dispersion in these layers depends on the size of particles and wavelength. The effective permittivity of the gravel aggregate (consisting of a layer in which rock particles, sand particles, pebbles, and air voids with diverse dispersion properties are arranged together) is determined as:

$$j\frac{\epsilon_0 - 1}{\epsilon_0 + 2\epsilon'}, \tag{9.13}$$

where j is the percentage of the solid material in the volume.

9.4.4 *Model Evaluations*

In this section, we present the path loss analysis. The model parameters considered for this evaluation are shown in Table 9.1. The soil and asphalt layer thickness are 20 and 10 cm, respectively, with soil moisture level of 5%. The operation frequency of 433 MHz is used with transmission power of 20 dBm. In Fig. 9.3, the propagation loss in the asphalt medium with change in layer thickness has been shown. It can be

Table 9.1 Model evaluation parameters [80]

Parameter	Value
P_t	20 dBm
Thickness of the soil layer	20 cm
Thickness of the asphalt layer	10 cm
Frequency	433 MHz
Noise floor	−90 dBm
Soil moisture	5% by Volume
Asphalt temperature	300 K/80.33 F/26 C

observed that with layer thickness of less than 1 m, the propagation loss is less than 5 dB. However, it increases with increase in layer thickness. It increases to 15 dB for the 4 m thick asphalt layer.

The path loss with change in distance is shown in Fig. 9.4. It can be observed that for communication distances up to 4 km, the path loss is less than 100 dB. It increases to 107 dB for a distance of 10 km. The received signal strength indicator (RSSI) with distance is shown in Fig. 9.5. It can be observed that the RSSI decreases with distance. This decrease is abrupt for distances less than 2 km. Afterwards, it decreases gradually. At communication distance of 4 km, the −80 dBm RSSI indicates that underground nodes in urban underground infrastructure monitoring IoT can effectively communicate with urban roadside wireless communication infrastructure.

In Fig. 9.6, the propagation loss in the soil medium with change in layer thickness has been shown. It can be observed that with layer thickness of less than 2 m, the propagation loss is less than 37 dB. However, it increases with increase in thickness. It increases to 57 dB for the 4 m thick soil layer. Moreover, it can also be observed that soil medium has higher loss as compared to the asphalt medium. This is caused by the higher permittivity of the soil as compared to the asphalt. The higher water holding capacity of the soil in comparison to asphalt medium leads to the higher permittivity of soil.

The effect of temperature change on propagation loss in asphalt is shown in Fig. 9.7. It can be observed that with change in asphalt temperature from 300 K to 360 K, the path loss increases to 3.6 dB. Therefore, the wireless communication system in urban underground infrastructure monitoring IoT should be designed by considering the temperature change of the asphalt medium in different weather conditions (Figs. 9.8 and 9.9).

9.5 Sensing and Sampling

In this section, different sensing related to water sampling needs are discussed. First the contaminant sensing is discussed (Figs. 9.10 and 9.11).

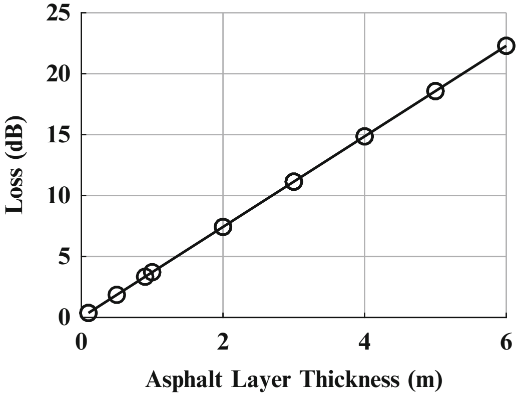


Fig. 9.7 The propagation loss in the asphalt medium with change in layer thickness [80]

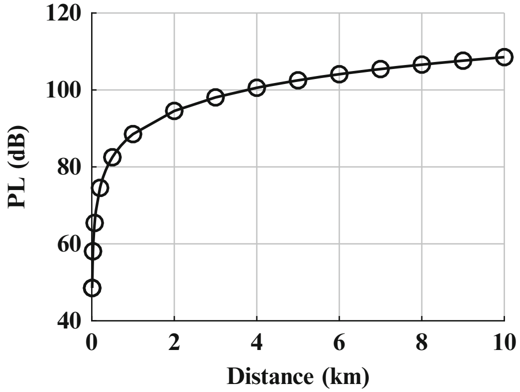


Fig. 9.8 The path loss with change in distance

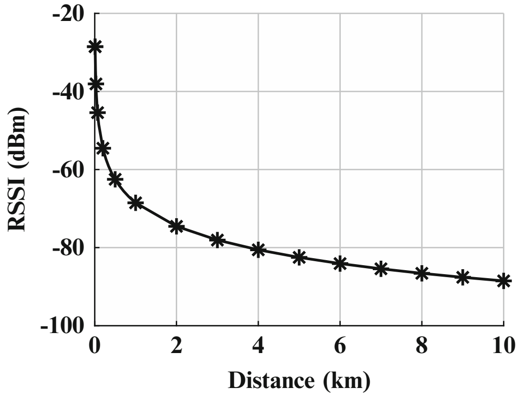


Fig. 9.9 The received signal strength indicator with distance [80]

Fig. 9.10 The propagation loss in the soil medium with change in layer thickness [80]

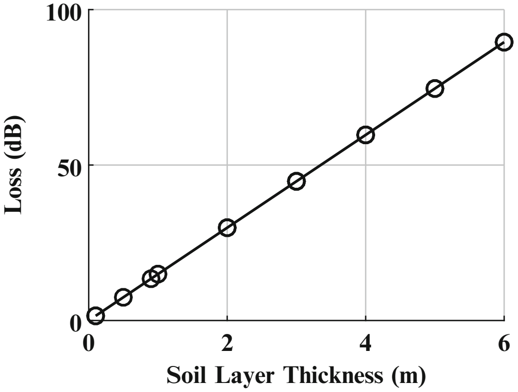
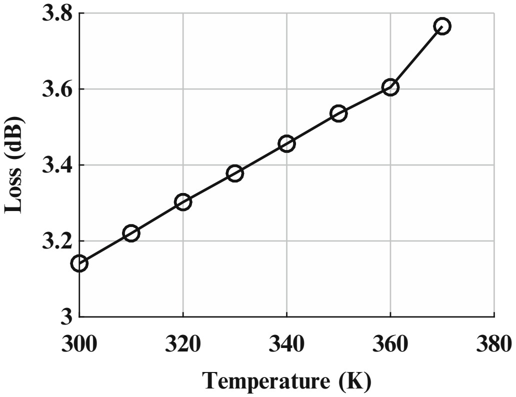


Fig. 9.11 The effect of temperature change on propagation loss in asphalt [80]



9.5.1 Contaminant Sensing

The contaminant sensing is not only important to detect the contaminants but it is also useful to assess the extent and nature of contaminants. The different contaminants in need of sensing are shown in Fig. 9.12.

9.5.2 Sensing for Wastewater Treatment and Reuse

Another important source of water supply is wastewater reuse, where water from different sources (e.g., industry, agriculture, and domestic) is collected, treated, and recycled to mitigate its detrimental impacts using multi-phase chemical, mechanical, and biological processes. The wastewater systems are also impacted by climate change [7, 27, 32]. Currently, the hazardous health environmental and health impacts of wastewater include its mixing with groundwater and surface water. Moreover, the health impacts resulting from consumption of this reclaimed water needs more investigation. Moreover, the advanced methods for removal of

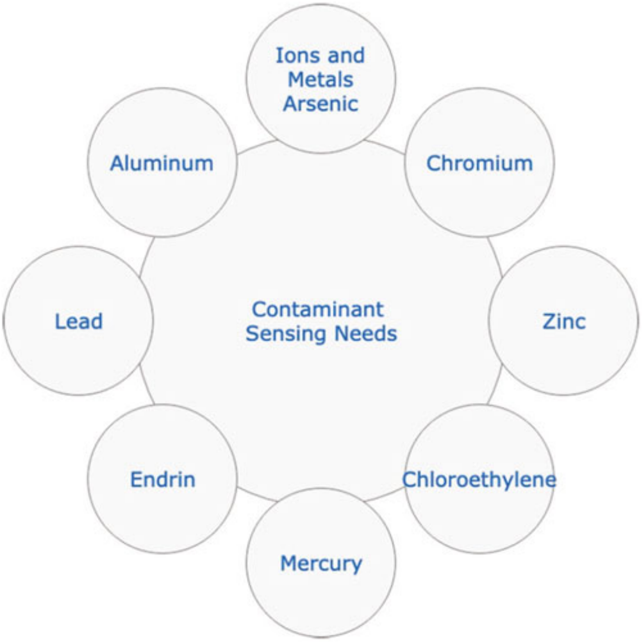


Fig. 9.12 The sensing needs for different contaminants

bacteria, analytes, their genes, micro-pollutants, byproducts, and residual materials are needed. A summary of site monitoring and characterization techniques for water is given below [31]:

- Anodic stripping voltammetry (ASV)
- Biosensors
- Colorimetric test kits
- Direct reading probes
- Electro-optical sensors
- Fiber optic chemical sensors (FOCS)
- Fourier Transform Infrared Spectroscopy (FTIR)
- Fuel Fluorescence Detector (FFD)
- GC-ion Mobility Spectrometry (IMS)
- Gas Chromatography (GC)
- Gas Chromatography/Mass Spectrometry (GC/MS)
- Graphite Furnace Atomic Absorption Spectrometry (GFAA)
- Gross counters
- Immunoassay test kits
- Inductively Coupled Plasma Spectrophotometry (ICP)
- Ion Selective Electrodes (ISE)
- Liquid Chromatography (LC)

- Membrane Interface Probes
- Mercury vapor analyzers
- Surface Acoustic Wave Sensors (SAWS)
- Ultraviolet fluorescence (UVF) test kits

9.5.3 Agricultural Hazards Sensing

The agriculture is becoming exceedingly vulnerable to the soil degradation, water scarcity, deteriorating mountain ecosystems, and more variable and intense weather patterns (e.g., floods, drought, frosts). However, there are major gaps in our understanding of changes in agriculture and how these changes will affect agriculture. Improved knowledge needs to be acquired to anticipate, plan, and adapt to these changes and to gain new grounds in agriculture. Furthermore, efforts are needed to develop better detection techniques for per- and poly-fluoroalkyl substances (PFAS), and PFAS-containing waste found in different soils. Among existing techniques, granular activated carbon (GAC) is a growing technology in PFAS treatment in water [17, 69]. However, there is a significant lack of data and procedure development in terms of fundamental understanding and quantification of medium properties. The adsorptive and destructive technologies are considered for both soils and waters [12, 21]. Other remediation approaches are anion-exchange, ozofractionation, chemical oxidation, electrochemical oxidation, sonolysis, soils stabilization, and thermal technologies [6, 45, 55, 64]. These treatment technologies are not best suited to provide PFAS management systems with almost real-time sensing data to facilitate fast decision-making [40, 44].

To meet the need of practical approaches to manage the potential environmental impacts of PFAS, environmental researchers must develop and implement new technologies to enhance detection and control of PFAS with fewer inputs. Enhanced techniques that are more practical and efficient in control, treatment, destruction, and removal of PFAS in soils are needed. This complex and arduous task requires interdisciplinary endeavors that combine various environmental science disciplines to develop such tools and implement them in the field to achieve this purpose. A summary of site monitoring and characterization techniques for soil is given below [31]:

- Colorimetric test kits. Test kits are self-contained analytical kits that generally use a chemical reaction that produces color to identify contaminants, both qualitatively and quantitatively [43].
- Fiber optic chemical sensors (FOCS). Fiber optic chemical sensors (FOCS) operate by transporting light by wavelength or intensity to provide information about analytes in the environment surrounding the sensor. The environment surrounding a FOCS is usually air or water. FOCS can be categorized as intrinsic or extrinsic. Extrinsic FOCS simply use an optical fiber to transport [109].

- Gas Chromatography (GC). Chromatography is the science of separation which uses a diverse group of methods to separate closely related components of complex mixtures. During gas chromatographic separation, the sample is transported via an inert gas called the mobile phase [16].
- Gas Chromatography/Mass Spectrometry (GC/MS). Mass spectrometry (MS) is an established analytical technique that identifies organic compounds by measuring the mass (more correctly, mass to charge ratio) of the compound's molecule. Mass spectrometry is noteworthy among analytical techniques because the signals produced by a spectrometer are the direct result of chemical reactions such as ionization and fragmentation, rather than energy state changes that are typical of most other spectroscopic techniques.
- Laser-induced Fluorescence (LIF). Laser-induced fluorescence (LIF) is a method for real-time, in situ field screening of residual and non-aqueous phase organic contaminants in undisturbed vadose, capillary fringe, and saturated subsurface soils and groundwater.
- Membrane Interface Probes. A MIP is a semi-quantitative, field screening device that can detect volatile organic compounds (VOCs) in soil and sediment. It is used in conjunction with a direct push platform (DPP), such as a cone penetrometer testing rig (CPT) or a rig that uses a hydraulic or pneumatic hammer to drive the MIP to the depth of interest to collect samples of vaporized compounds.
- X-ray fluorescence (XRF). XRF instruments are field-portable or handheld devices for simultaneously measuring metals and other elements in various media.
- Direct reading probes
- Downhole pyrolysis explosives sensor
- Electromagnetic induction (EM)
- Fourier Transform Infrared Spectroscopy (FTIR)
- Fuel Fluorescence Detector (FFD)
- GC-ion Mobility Spectrometry (IMS)
- Graphite Furnace Atomic Absorption Spectrometry (GFAA)
- Gross counters
- Ground Penetrating Radar (GPR)
- Immunoassay test kits
- Inductively Coupled Plasma Spectrophotometry (ICP)
- Ion Selective Electrodes (ISE)
- Laser-induced Breakdown Spectroscopy (LIBS)
- Liquid Chromatography (LC)
- Magnetometry
- Mercury vapor analyzers
- Seismic reflection/refraction
- Soil/sediment micro-heterogeneity management to improve data precision
- Surface Acoustic Wave Sensors (SAWS)
- Ultraviolet fluorescence (UVF) test kits

References

1. Adamchuk, V., Hummel, J., Morgan, M., & Upadhyaya, S. (2004). On-the-go soil sensors for precision agriculture. *Computers and Electronics in Agriculture, 44*(1), 71–91.
2. Agel, L., Barlow, M., Colby, F., Binder, H., Catto, J.L., Hoell, A., et al. (2019). Dynamical analysis of extreme precipitation in the US northeast based on large-scale meteorological patterns. *Climate Dynamics, 52*(3–4), 1739–1760.
3. Akyildiz, I. F., & Stuntebeck, E. P. (2006). Wireless underground sensor networks: Research challenges. *Ad Hoc Networks Journal, 4*, 669–686.
4. Akyildiz, I. F., Sun, Z., & Vuran, M. C. (2009). Signal propagation techniques for wireless underground communication networks. *Physical Communication Journal, 2*(3), 167–183.
5. Alexander, L., Zhang, X., Peterson, T., Caesar, J., Gleason, B., Klein Tank, A., et al. (2006). Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research: Atmospheres, 111*(D5), 1–22.
6. Allred, B. M., Lang, J. R., Barlaz, M. A., & Field, J.A. (2014). Orthogonal zirconium diol/C18 liquid chromatography–tandem mass spectrometry analysis of poly and perfluoroalkyl substances in landfill leachate. *Journal of Chromatography A, 1359*, 202–211.
7. American Water Works Association (AWWA). (2010). *Risk and resilience management of water and wastewater systems*. Denver: American Water Works Association.
8. American Water Works Association (AWWA). (2015). *Water/wastewater agency response network (warn)*. Denver: American Water Works Association.
9. Andjelkovic, I. (2001). Guidelines on non-structural measures in urban flood management. Technical Report. International Hydrological Programme (IHP), United Nations Educational, Scientific and Cultural Organization.
10. Arvai, A., Klecka, G., Jasim, S., Melcer, H., & Laitta, M. (2013). Protecting our great lakes: Assessing the effectiveness of wastewater treatments for the removal of chemicals of emerging concern. *Water Quality Research Journal of Canada 49*(1), 23–31. https://doi.org/10.2166/wqrjc.2013.104. Cited By 8.
11. Asano, T., & Cotruvo, J. (2004). Groundwater recharge with reclaimed municipal wastewater: Health and regulatory considerations. *Water Research 38*(8), 1941–1951. https://doi.org/10.1016/j.watres.2004.01.023. Cited By 236.
12. Backe, W. J., Day, T. C., & Field, J. A. (2013). Zwitterionic, cationic, and anionic fluorinated chemicals in aqueous film forming foam formulations and groundwater from US military bases by nonaqueous large-volume injection HPLC-MS/MS. *Environmental Science & Technology, 47*(10), 5226–5234.
13. Backer, L., & Moore, S. (2010). Harmful algal blooms: future threats in a warmer world. In A. Nemr (Ed.), *Environmental pollution and its relation to climate change* (pp. 485–512).
14. Bakker, K. (2012). Water security: research challenges and opportunities. *Science, 337*(6097), 914–915.
15. Balci, P., & Cohn, A. (2014). NYC wastewater resiliency plan: Climate risk assessment and adaptation. In *ICSI 2014: Creating infrastructure for a sustainable world* (pp. 246–256).
16. Bellar, T. A., Lichtenberg, J. J., & Kroner, R. C. (1974). The occurrence of organohalides in chlorinated drinking waters. *Journal-American Water Works Association, 66*(12), 703–706.
17. Benskin, J. P., Li, B., Ikonomou, M. G., Grace, J. R., & Li, L. Y. (2012). Per-and polyfluoroalkyl substances in landfill leachate: patterns, time trends, and sources. *Environmental Science & Technology, 46*(21), 11532–11540.
18. Bogena, H. R., Herbst, M., Huisman, J. A., Rosenbaum, U., Weuthen, A., & Vereecken, H. (2010). Potential of wireless sensor networks for measuring soil water content variability. *Vadose Zone Journal, 9*(4), 1002–1013.
19. Bredehoeft, J. (2011). Monitoring regional groundwater extraction: The problem. *Groundwater, 49*(6), 808–814.

20. Brikowski, T. H. (2008). Doomed reservoirs in Kansas, USA? Climate change and groundwater mining on the great plains lead to unsustainable surface water storage. *Journal of hydrology, 354*(1–4), 90–101.
21. Buck, R. C., Franklin, J., Berger, U., Conder, J.M., Cousins, I.T., De Voogt, P., et al. (2011). Perfluoroalkyl and polyfluoroalkyl substances in the environment: Terminology, classification, and origins. *Integrated Environmental Assessment and Management, 7*(4), 513–541.
22. Burleson, G., Tilt, B., Sharp, K., & MacCarty, N. (2019). Reinventing boiling: A rapid ethnographic and engineering evaluation of a high-efficiency thermal water treatment technology in Uganda. *Energy Research & Social Science, 52*, 68–77.
23. Cannon, F., Carvalho, L. M., Jones, C., Hoell, A., Norris, J., Kiladis, G.N., et al. (2017). The influence of tropical forcing on extreme winter precipitation in the Western Himalaya. *Climate Dynamics, 48*(3–4), 1213–1232.
24. Casanova, J., Devau, N., & Pettenati, M. (2016). Managed aquifer recharge: An overview of issues and options. In *Integrated groundwater management*. Cham: Springer. Cited By 8.
25. Catarci, T., Dix, A., Kimani, S., & Santucci, G. (2010). User-centered data management. *Synthesis Lectures on Data Management 2*(1), 1–106.
26. Chen, J., Broussard, W. P., Borrok, D. M., & Speyrer, F. B. (2019). A GIS-based framework to identify opportunities to use surface water to offset groundwater withdrawals. *Water Resources Management*, 1–11.
27. Cromwell, J., & McGuckin, R. (2010). Implications of climate change for adaptation by wastewater and stormwater agencies. *Proceedings of the Water Environment Federation, 2010*(15), 1887–1915.
28. DeZellar, J., & Maier, W. (1980). Effects of water conservation on sanitary sewers and wastewater treatment plants. *Journal of the Water Pollution Control Federation, 52*(1), 76–88. Cited By 12.
29. Dhasmana, A., Uniyal, S., Kumar, V., Gupta, S., Kesari, K.K., Haque, S., et al. (2019). Scope of nanoparticles in environmental toxicant remediation. In *Environmental Biotechnology: For Sustainable Future* (pp. 31–44). Berlin: Springer.
30. Dong, X., Vuran, M. C., & Irmak, S. (2013). Autonomous precision agriculture through integration of wireless underground sensor networks with center pivot irrigation systems. *Ad Hoc Networks, 11*(7), 1975–1987. https://doi.org/10.1016/j.adhoc.2012.06.012.
31. EPA clean-up information. https://clu-in.org/remediation/.
32. Flood, J. F., & Cahoon, L. B. (2011). Risks to coastal wastewater collection systems from sea-level rise and climate change. *Journal of Coastal Research, 27*(4), 652–660.
33. Gain, A., Giupponi, C., & Wada, Y. (2016). Measuring global water security towards sustainable development goals. *Environmental Research Letters, 11*(12). https://doi.org/10.1088/1748-9326/11/12/124015. Cited By 18.
34. Gallopín, G. The United Nations World Water Development Report – N° 4 – Global Water Futures 2050: Five Stylized Scenarios. UNESCO.
35. Garrison, N., & Hobbs, K. (2011). *Rooftops to rivers ii: Green strategies for controlling stormwater and combined sewer overflows* (pp. 1–134). New York, NY: Natural Resources Defense Council.
36. Glibert, P. M., Anderson, D. M., Gentien, P., Granéli, E., & Sellner, K. G. (2005). The global, complex phenomena of harmful algal blooms. *Oceanography, 18*(2), 136–147.
37. Goldsmith, A. (2005). *Wireless communications*. New York, NY: Cambridge University Press.
38. Gunda, T., Hess, D., Hornberger, G. M., & Worland, S. (2019). Water security in practice: The quantity-quality-society nexus. *Water Security, 6*, 100022.
39. Guo, H., & Sun, Z. (2014). Channel and energy modeling for self-contained wireless sensor networks in oil reservoirs. *IEEE Transactions Wireless Communications, 13*(4), 2258–2269. https://doi.org/10.1109/TWC.2013.031314.130835.
40. Hamid, H., Li, L. Y., & Grace, J. R. (2018). Review of the fate and transformation of per-and polyfluoroalkyl substances (PFASs) in landfills. *Environmental Pollution, 235*, 74–84.

41. Hamill, T. M., Engle, E., Myrick, D., Peroutka, M., Finan, C., & Scheuerer, M. (2017). The US national blend of models for statistical postprocessing of probability of precipitation and deterministic precipitation amount. *Monthly Weather Review, 145*(9), 3441–3463.
42. Hoekstra, A. Y., Buurman, J., & van Ginkel, K. C. (2018). Urban water security: A review. *Environmental Research Letters, 13*(5), 053002.
43. Hofstetter, J. C., Wydallis, J. B., Neymark, G., Reilly III, T. H., Harrington, J., & Henry, C. S. (2018). Quantitative colorimetric paper analytical devices based on radial distance measurements for aqueous metal determination. *Analyst, 143*(13), 3085–3090.
44. Hu, X. C., Andrews, D. Q., Lindstrom, A. B., Bruton, T. A., Schaider, L. A., Grandjean, P., et al. (2016). Detection of poly-and perfluoroalkyl substances (PFASs) in US drinking water linked to industrial sites, military fire training areas, and wastewater treatment plants. *Environmental Science & Technology Letters, 3*(10), 344–350.
45. Huset, C. A., Barlaz, M. A., Barofsky, D. F., & Field, J. A. (2011). Quantitative determination of fluorochemicals in municipal landfill leachates. *Chemosphere, 82*(10), 1380–1386.
46. Hutchins, M. G., McGrane, S. J., Miller, J. D., Hagen-Zanker, A., Kjeldsen, T. R., Dadson, S. J., et al. (2017). Integrated modeling in urban hydrology: reviewing the role of monitoring technology in overcoming the issue of 'big data' requirements. *Wiley Interdisciplinary Reviews: Water, 4*(1), e1177.
47. Ji, Y., Dong, C., Kong, D., Lu, J., & Zhou, Q. (2015). Heat-activated persulfate oxidation of atrazine: implications for remediation of groundwater contaminated by herbicides. *Chemical Engineering Journal, 263*, 45–54.
48. Johnk, C. T. (1988). *Engineering electromagnetic fields and waves* (2nd ed.). Hoboken: John Wiley & Sons.
49. Kessler, R. (2011). Stormwater strategies: cities prepare aging infrastructure for climate change. *Environ Health Perspect, 119*(12), 514–519. https://doi.org/10.1289/ehp.119-a514.
50. Konda, A., Rau, A., Stoller, M. A., Taylor, J. M., Salam, A., Pribil, G. A., et al. (2018). Soft microreactors for the deposition of conductive metallic traces on planar, embossed, and curved surfaces. *Advanced Functional Materials, 28*(40), 1803020. https://doi.org/10.1002/adfm.201803020.
51. Koo, D., Piratla, K., & Matthews, C. J. (2015). Towards sustainable water supply: schematic development of big data collection using internet of things (IoT). *Procedia Engineering, 118*, 489–497.
52. Li, X.-q., Elliott, D. W., & Zhang, W.-x. (2006). Zero-valent iron nanoparticles for abatement of environmental pollutants: Materials and engineering aspects. *Critical Reviews in Solid State and Materials Sciences, 31*(4), 111–122.
53. Luo, L., Apps, D., Arcand, S., Xu, H., Pan, M., & Hoerling, M. (2017). Contribution of temperature and precipitation anomalies to the California drought during 2012–2015. *Geophysical Research Letters, 44*(7), 3184–3192.
54. Markham, A., & Trigoni, N. (2012). Magneto-inductive networked rescue system (MINERS): Taking sensor networks underground. In *Proceedings of the 11th ICPS, IPSN '12* (pp. 317–328). New York: ACM. https://doi.org/10.1145/2185677.2185746.
55. Merino, N., Qu, Y., Deeb, R. A., Hawley, E. L., Hoffmann, M. R., & Mahendra, S. (2016). Degradation and removal methods for perfluoroalkyl and polyfluoroalkyl substances in water. *Environmental Engineering Science, 33*(9), 615–649.
56. Moore, S. K., Trainer, V. L., Mantua, N. J., Parker, M. S., Laws, E. A., Backer, L. C., et al. (2008). Impacts of climate variability and future climate change on harmful algal blooms and human health. In *Environmental health* (Vol. 7, p. S4). London: BioMed Central.
57. Mulligan, C., Yong, R., & Gibbs, B. (2001). Remediation technologies for metal-contaminated soils and groundwater: an evaluation. *Engineering Geology, 60*(1–4), 193–207.
58. National Research Council. (2012). *Water reuse: Potential for expanding the nation's water supply through reuse of municipal wastewater*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13303. Cited By 44.

59. Nilsen, V., Lier, J., Bjerkholt, J., & Lindholm, O. (2011). Analysing urban floods and combined sewer overflows in a changing climate. *Journal of Water and Climate Change, 2*(4), 260–271.
60. Nyer, E. K. (2019). *Practical techniques for groundwater & soil remediation*. New York: Routledge.
61. Peplinski, N. R., Ulaby, F. T., & Dobson, M. C. (1995). Dielectric properties of soils in the 0.3-1.3-GHz range. In *IEEE transactions on geoscience and remote sensing*, vol. 33(3) (pp. 803–807). https://doi.org/10.1109/36.387598.
62. Pilon, B. S., Tyner, J. S., Yoder, D. C., & Buchanan, J. R. (2019). The effect of pervious concrete on water quality parameters: a case study. *Water, 11*(2), 263.
63. Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., et al. (1997). The natural flow regime. *BioScience, 47*(11), 769–784.
64. Rahman, M. F., Peldszus, S., & Anderson, W. B. (2014). Behaviour and fate of perfluoroalkyl and polyfluoroalkyl substances (PFASs) in drinking water treatment: A review. *Water Research, 50*, 318–340.
65. Rao, P. S. C., Annable, M. D., Sillan, R. K., Dai, D., Hatfield, K., Graham, W. D., et al. (1997). Field-scale evaluation of in situ cosolvent flushing for enhanced aquifer remediation. *Water Resources Research, 33*(12), 2673–2686.
66. Rice, J., & Westerhoff, P. (2015). Spatial and temporal variation in de facto wastewater reuse in drinking water systems across the USA. *Environmental Science and Technology, 49*(2), 982–989. https://doi.org/10.1021/es5048057. Cited By 43.
67. Robles, T., Alcarria, R., de Andrés, D. M., de la Cruz, M. N., Calero, R., Iglesias, S., et al. (2015). An IoT based reference architecture for smart water management processes. *JoWUA, 6*(1), 4–23.
68. Robles, T., Alcarria, R., Martín, D., Morales, A., Navarro, M., Calero, R., et al. (2014). An internet of things-based model for smart water management. In: *2014 28th International Conference on Advanced Information Networking and Applications Workshops* (pp. 821–826). Piscataway: IEEE.
69. Ross, I., McDonough, J., Miles, J., Storch, P., Thelakkat Kochunarayanan, P., Kalve, E., et al. (2018). A review of emerging technologies for remediation of PFASs. *Remediation Journal, 28*(2), 101–126.
70. Saeed, N., Alouini, M. S., & Al-Naffouri, T. Y. (2019). 3D localization for internet of underground things in oil and gas reservoirs. *IEEE Access, 7*, 121769–121780.
71. Saeed, N., Alouini, M. S., & Al-Naffouri, T. Y. (2019). Towards the internet of underground things: A systematic survey. IEEE Communications Surveys & Tutorials.
72. Salam, A. (2018). *Pulses in the sand: Long range and high data rate communication techniques for next generation wireless underground networks*. Lincoln: ETD collection for University of Nebraska (AAI10826112). http://digitalcommons.unl.edu/dissertations/AAI10826112.
73. Salam, A. (2019). A comparison of path loss variations in soil using planar and dipole antennas. In *2019 IEEE International Symposium on Antennas and Propagation*. Piscataway: IEEE.
74. Salam, A. (2019). A path loss model for through the soil wireless communications in digital agriculture. In *2019 IEEE International Symposium on Antennas and Propagation*. Piscataway: IEEE.
75. Salam, A. (2019). Subsurface MIMO: A beamforming design in internet of underground things for digital agriculture applications. *Journal of Sensor and Actuator Networks, 8*(3). https://doi.org/10.3390/jsan8030041.
76. Salam, A. (2019). Underground environment aware MIMO design using transmit and receive beamforming in internet of underground things. In *2019 International Conference on Internet of Things (ICIOT 2019)*, San Diego.
77. Salam, A. (2019). An underground radio wave propagation prediction model for digital agriculture. *Information, 10*(4). https://doi.org/10.3390/info10040147.

78. Salam, A. (2019). Underground soil sensing using subsurface radio wave propagation. In *5th Global Workshop on Proximal Soil Sensing*, Columbia.
79. Salam, A., & Shah, S. (2019). Internet of things in smart agriculture: Enabling technologies. In *2019 IEEE 5th World Forum on Internet of Things (WF-IoT) (WF-IoT 2019)*, Limerick.
80. Salam, A., & Shah, S. (2019). Urban underground infrastructure monitoring IoT: The path loss analysis. In *2019 IEEE 5th World Forum on Internet of Things (WF-IoT) (WF-IoT 2019)*, Limerick.
81. Salam, A., & Vuran, M. C. (2017). Smart underground antenna arrays: A soil moisture adaptive beamforming approach. In *Proceedings of IEEE INFOCOM 2017*, Atlanta.
82. Salam, A., & Vuran, M. C. (2017). Wireless underground channel diversity reception with multiple antennas for internet of underground things. In *Proceedings of IEEE ICC 2017*, Paris.
83. Salam, A., & Vuran, M. C. (2018). EM-based wireless underground sensor networks. In S. Pamukcu, L. Cheng (Eds.) *Underground Sensing* (pp. 247–285). Cambridge: Academic Press. https://doi.org/10.1016/B978-0-12-803139-1.00005-9.
84. Salam, A., Vuran, M. C., Dong, X., Argyropoulos, C., & Irmak, S. (2019). A theoretical model of underground dipole antennas for communications in internet of underground things. *IEEE Transactions on Antennas and Propagation, 67*(6), 3996–4009.
85. Salam, A., Vuran, M. C., & Irmak, S. (2016). Pulses in the sand: Impulse response analysis of wireless underground channel. In *Proceedings of INFOCOM 2016*, San Francisco.
86. Salam, A., Vuran, M. C., & Irmak, S. (2017). Towards internet of underground things in smart lighting: A statistical model of wireless underground channel. In *Proceedings of 14th IEEE International Conference on Networking, Sensing and Control (IEEE ICNSC)*, Calabria.
87. Salam, A., Vuran, M. C., & Irmak, S. (2019). Di-sense: In situ real-time permittivity estimation and soil moisture sensing using wireless underground communications. *Computer Networks, 151*, 31–41. https://doi.org/10.1016/j.comnet.2019.01.001.
88. Sanders, D. A. (1997). Damage to wastewater treatment facilities from great flood of 1993. *Journal of Environmental Engineering, 123*(1), 54–60.
89. Scibek, J., Allen, D. M., Cannon, A. J., & Whitfield, P. H. (2007). Groundwater–surface water interaction under scenarios of climate change using a high-resolution transient groundwater model. *Journal of Hydrology, 333*(2–4), 165–181.
90. Sinha, S. K., & Knight, M. A. (2004). Intelligent system for condition monitoring of underground pipelines. *Computer-Aided Civil and Infrastructure Engineering, 19*(1), 42–53.
91. Sun, Z., & Akyildiz, I. (2010). Channel modeling and analysis for wireless networks in underground mines and road tunnels. *IEEE Transactions on Communications, 58*(6), 1758–1768. https://doi.org/10.1109/TCOMM.2010.06.080353.
92. Sun, Z., Wang, P., Vuran, M. C., Al-Rodhaan, M. A., Al-Dhelaan, A. M., & Akyildiz, I. F. (2011). MISE-PIPE: Magnetic induction-based wireless sensor networks for underground pipeline monitoring. *Ad Hoc Networks, 9*(3), 218–227.
93. Sun, Z., Wang, P., Vuran, M. C., Al-Rodhaan, M. A., Al-Dhelaan, A. M., & Akyildiz, I. F. (2011). Border patrol through advanced wireless sensor networks. *Ad Hoc Networks, 9*(3), 468–477.
94. Temel, S., Vuran, M. C., Lunar, M. M., Zhao, Z., Salam, A., Faller, R. K., et al. (2018). Vehicle-to-barrier communication during real-world vehicle crash tests. *Computer Communications, 127*, 172–186. https://doi.org/10.1016/j.comcom.2018.05.009.
95. Teschke, K., Bellack, N., Shen, H., Atwater, J., Chu, R., Koehoorn, M., et al. (2010). Water and sewage systems, socio-demographics, and duration of residence associated with endemic intestinal infectious diseases: A cohort study. *BMC Public Health, 10*(1), 767.
96. Tiusanen, M. J. (2013). Soil scouts: Description and performance of single hop wireless underground sensor nodes. *Ad Hoc Networks, 11*(5), 1610–1618. http://doi.org/10.1016/j.adhoc.2013.02.002.
97. Tratnyek, P. G., & Johnson, R. L. (2006). Nanotechnologies for environmental cleanup. *Nano Today, 1*(2), 44–48.

98. Trenberth, K. E. (2011). Changes in precipitation with climate change. *Climate Research, 47*(1–2), 123–138.
99. Trenberth, K. E., Zhang, Y., & Gehne, M. (2017). Intermittency in precipitation: Duration, frequency, intensity, and amounts using hourly data. *Journal of Hydrometeorology, 18*(5), 1393–1412.
100. Tsitonaki, A., Petri, B., Crimi, M., Mosbæk, H., Siegrist, R. L., & Bjerg, P. L. (2010). In situ chemical oxidation of contaminated soil and groundwater using persulfate: A review. *Critical Reviews in Environmental Science and Technology, 40*(1), 55–91.
101. Tuohy, P., O'Loughlin, J., Peyton, D., & Fenton, O. (2018). The performance and behavior of land drainage systems and their impact on field scale hydrology in an increasingly volatile climate. *Agricultural Water Management, 210*, 96–107.
102. Tuomela, C., Sillanpää, N., & Koivusalo, H. (2019). Assessment of stormwater pollutant loads and source area contributions with storm water management model (SWMM). *Journal of Environmental Management, 233*, 719–727.
103. U.S. Department of the Interior Advisory Committee on Water Information, S.o.G.: A national framework for ground-water monitoring in the U.S. (2013).
104. Vuran, M., Dong, X., & Anthony, D. (2016). Antenna for wireless underground communication. https://www.google.com/patents/US9532118. US Patent 9532118.
105. Vuran, M. C., & Akyildiz, I. F. (2010). Channel model and analysis for wireless underground sensor networks in soil medium. *Physical Communication, 3*(4), 245–254. https://doi.org/10.1016/j.phycom.2010.07.001.
106. Vuran, M. C., Salam, A., Wong, R., & Irmak, S. (2018). Internet of underground things in precision agriculture: Architecture and technology aspects. *Ad Hoc Networks, 81*, 160–173. https://doi.org/10.1016/j.adhoc.2018.07.017.
107. Vuran, M. C., Salam, A., Wong, R., & Irmak, S. (2018). Internet of underground things: Sensing and communications on the field for precision agriculture. In *2018 IEEE 4th World Forum on Internet of Things (WF-IoT) (WF-IoT 2018)*, Singapore.
108. Wait, J., & Fuller, J. (1971). On radio propagation through earth: Antennas and propagation. *IEEE Transactions Antennas and Propagation, 19*(6), 796–798.
109. Wang, X. D., & Wolfbeis, O. S. (2012). Fiber-optic chemical sensors and biosensors (2008–2012). *Analytical Chemistry, 85*(2), 487–508.
110. Weiser, M. (2018). *Recycled wastewater at your tap? It could be soon in Arizona*. New York: News Deeply. Cited By 1.
111. Zhang, X., Zwiers, F. W., Hegerl, G. C., Lambert, F. H., Gillett, N. P., Solomon, S., et al. (2007). Detection of human influence on twentieth-century precipitation trends. *Nature, 448*(7152), 461.
112. Zhang, Y., Sivakumar, M., Yang, S., Enever, K., & Ramezanianpour, M. (2018). Application of solar energy in water treatment processes: A review. *Desalination, 428*, 116–145.
113. Salam A. (2020) Internet of Things for Sustainable Community Development: Introduction and Overview. In: Internet of Things for Sustainable Community Development. Internet of Things (Technology, Communications and Computing). Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-35291-2_1
114. Salam A. (2020) Internet of Things for Environmental Sustainability and Climate Change. In: Internet of Things for Sustainable Community Development. Internet of Things (Technology, Communications and Computing). Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-35291-2_2
115. Salam A. (2020) Internet of Things in Agricultural Innovation and Security. In: Internet of Things for Sustainable Community Development. Internet of Things (Technology, Communications and Computing). Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-35291-2_3
116. Salam A. (2020) Internet of Things for Water Sustainability. In: Internet of Things for Sustainable Community Development. Internet of Things (Technology, Communications and Computing). Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-35291-2_4
117. Salam A. (2020) Internet of Things for Sustainable Forestry. In: Internet of Things for Sustainable Community Development. Internet of Things (Technology, Communications and Computing). Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-35291-2_5

98. Salam A. (2020) Internet of Things in Sustainable Energy Systems. In: Internet of Things for Sustainable Community Development. Internet of Things (Technology, Communications and Computing). Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-35291-2_6
99. Salam A. (2020) Internet of Things for Sustainable Human Health. In: Internet of Things for Sustainable Community Development. Internet of Things (Technology, Communications and Computing). Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-35291-2_7
100. Salam A. (2020) Internet of Things for Sustainable Mining. In: Internet of Things for Sustainable Community Development. Internet of Things (Technology, Communications and Computing). Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-35291-2_8
101. Salam A. (2020) Internet of Things in Water Management and Treatment. In: Internet of Things for Sustainable Community Development. Internet of Things (Technology, Communications and Computing). Springer, Cham. 10.1007/978-3-030-35291-2_9
102. Salam A. (2020) Internet of Things for Sustainability: Perspectives in Privacy, Cybersecurity, and Future Trends. In: Internet of Things for Sustainable Community Development. Internet of Things (Technology, Communications and Computing). Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-35291-2_10
103. Salam, A.; Hoang, A.D.; Meghna, A.; Martin, D.R.; Guzman, G.; Yoon, Y.H.; Carlson, J.; Kramer, J.; Yansi, K.; Kelly, M.; Skvarek, M.; Stankovic, M.; Le, N.D.K.; Wierzbicki, T.; Fan, X. The Future of Emerging IoT Paradigms: Architectures and Technologies. Preprints 2019, 2019120276 (doi: https://doi.org/10.20944/preprints201912.0276.v1).
104. A. Konda, A. Rau, M. A. Stoller, J. M. Taylor, A. Salam, G. A. Pribil, C. Argyropoulos, and S. A. Morin, “Soft microreactors for the deposition of conductive metallic traces on planar, embossed, and curved surfaces,” Advanced Functional Materials, vol. 28, no. 40, p. 1803020. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/adfm.201803020
105. A. Salam, M. C. Vuran, and S. Irmak, “Pulses in the sand: Impulse response analysis of wireless underground channel,” in The 35th Annual IEEE International Conference on Computer Communications (INFOCOM 2016), San Fran- cisco, USA, Apr. 2016.
106. A. Salam and M. C. Vuran, “Impacts of soil type and moisture on the capacity of multi-carrier modulation in internet of underground things,” in Proc. of the 25th ICCCN 2016, Waikoloa, Hawaii, USA, Aug 2016.
107. A. Salam, M. C. Vuran, and S. Irmak, “Towards internet of underground things in smart lighting: A statistical model of wireless underground channel,” in Proc. 14th IEEE International Conference on Networking, Sensing and Control (IEEE ICNSC), Calabria, Italy, May 2017.
108. A. Salam and M. C. Vuran, “Smart underground antenna arrays: A soil moisture adaptive beamforming approach,” in Proc. IEEE INFOCOM 2017, Atlanta, USA, May 2017.
109. ——, “Wireless underground channel diversity reception with multiple antennas for internet of underground things,” in Proc. IEEE ICC 2017, Paris, France, May 2017.
110. ——, “EM-Based Wireless Underground Sensor Networks,” in Underground Sensing, S. Pamukcu and L. Cheng, Eds. Academic Press, 2018, pp. 247 – 285.
111. A. Salam, M. C. Vuran, and S. Irmak, “Di-sense: In situ real- time permittivity estimation and soil moisture sensing using wireless underground communications,” Computer Networks, vol. 151, pp. 31 – 41, 2019. [Online]. Available: http://www.sciencedirect.com/science/article/pii/ S1389128618303141
112. A. Salam and S. Shah, “Urban underground infrastructure monitoring IoT: the path loss analysis,” in 2019 IEEE 5th World Forum on Internet of Things (WF- IoT) (WF-IoT 2019), Limerick, Ireland, Apr. 2019.
113. A. Salam, “Pulses in the sand: Long range and high data rate communication techniques for next generation wireless underground networks,” ETD collection for University of Nebraska - Lincoln, no. AAI10826112, 2018. [Online]. Available: http://digitalcommons.unl.edu/dissertations/AAI10826112
114. A. Salam and S. Shah, “Internet of things in smart agriculture: Enabling technologies,” in 2019 IEEE 5th World Forum on Internet of Things (WF-IoT) (WF-IoT 2019), Limerick, Ireland, Apr. 2019.
115. A. Salam, M. C. Vuran, X. Dong, C. Argyropoulos, and S. Irmak, “A theoretical model of underground dipole antennas for communications in internet of under- ground things,” IEEE Transactions on Antennas and Propagation, 2019.

98. A. Salam, “Underground soil sensing using subsurface radio wave propagation,” in 5th Global Workshop on Proximal Soil Sensing, COLUMBIA, MO, May 2019.
99. ——, Underground Environment Aware MIMO Design Using Transmit and Receive Beamforming in Internet of Underground Things. Cham: Springer International Publishing, 2019, pp. 1–15.
100. A. Salam and U. Karabiyik, “A cooperative overlay approach at the physical layer of cognitive radio for digital agriculture,” in Third International Balkan Conference on Communications and Networking 2019 (BalkanCom’19), Skopje, Macedonia, the former Yugoslav Republic of, Jun. 2019.
101. A. Salam, “An underground radio wave propagation prediction model for digital agriculture,” Information, vol. 10, no. 4, 2019. [Online]. Available: http://www.mdpi.com/2078-2489/10/4/147
102. S. Temel, M. C. Vuran, M. M. Lunar, Z. Zhao, A. Salam, R. K. Faller, and C. Stolle, “Vehicle-to-barrier communication during real-world vehicle crash tests,” Computer Communications, vol. 127, pp. 172 – 186, 2018. [Online]. Available: http://www.sciencedirect.com/science/article/pii/ S0140366417305224
103. M. C. Vuran, A. Salam, R. Wong, and S. Irmak, “Internet of underground things: Sensing and communications on the field for precision agriculture,” in 2018 IEEE 4th World Forum on Internet of Things (WF-IoT) (WF-IoT 2018), Singapore, Feb. 2018.
104. ——, “Internet of underground things in precision agriculture: Architecture and technology aspects,” Ad Hoc Networks, 2018.
105. A. Salam, "A Path Loss Model for Through the Soil Wireless Communications in Digital Agriculture", in Proc. 2019 IEEE International Symposium on Antennas and Propagation (IEEE APS 2019), Atlanta, GA, USA, July 2019.
106. A. Salam, "A Comparison of Path Loss Variations in Soil using Planar and Dipole Antennas", in Proc. 2019 IEEE International Symposium on Antennas and Propagation (IEEE APS 2019), Atlanta, GA, USA, July 2019.
107. Salam A. (2020) Internet of Things for Sustainable Community Development. Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-35291-2
108. A. Salam, "Design of Subsurface Phased Array Antennas for Digital Agriculture Applications", in Proc. 2019 IEEE International Symposium on Phased Array Systems and Technology (IEEE Array 2019), Waltham, MA, USA, Oct 2019.
109. A. Salam, "Subsurface MIMO: A Beamforming Design in Internet of Underground Things for Digital Agriculture Applications", J. Sens. Actuator Netw., Volume 8, No. 3, August 2019. doi: 10.3390/jsan8030041