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Review

A Review of Underground Pipeline Leakage and Sinkhole Monitoring Methods Based on Wireless Sensor Networking

Haibat Ali and Jae-ho Choi *

Civil Engineering, Dong-A University, Busan, P4401-1, 550 Bungil 37, Nakdong-Dero, Saha-Gu 49315, Korea
* Correspondence: jaehochoi@dau.ac.kr; Tel.: +82-51-200-762

Received: 9 July 2019; Accepted: 21 July 2019; Published: 24 July 2019

Abstract: Major metropolitan cities worldwide have extensively invested to secure utilities and build state-of-the-art infrastructure related to underground fluid transportation. Sewer and water pipelines make our lives extremely convenient when they function appropriately. However, leakages in underground pipe mains causes sinkholes and drinking-water scarcity. Sinkholes are the complex problems stemming from the interaction of leaked water and ground. The aim of this work is to review the existing methods for monitoring leakage in underground pipelines, the sinkholes caused by these leakages, and the viability of wireless sensor networking (WSN) for monitoring leakages and sinkholes. Herein, the authors have discussed the methods based on different objectives and their applicability via various approaches—(1) patent analysis; (2) web-of-science analysis; (3) WSN-based pipeline leakage and sinkhole monitoring. The study shows that the research on sinkholes due to leakages in sewer and water pipelines by using WSN is still in a premature stage and needs extensive investigation and research contributions. Additionally, the authors have suggested prospects for future research by comparing, analyzing, and classifying the reviewed methods. This study advocates collocating WSN, Internet of things, and artificial intelligence with pipeline monitoring methods to resolve the issues of the sinkhole occurrence.

Keywords: WSN; pipeline leakage; human-induced sinkhole; leakage detection; sewer pipeline; sensors

1. Introduction

Sewer and water leakages in underground pipelines have become a critical issue for water-management authorities in most countries—developed and developing alike—worldwide. Leakages in sewer and water pipelines may lead to several problems such as a shortage of drinking water, groundwater contamination, and ground subsidence [1]. Numerous countries are investing a considerable amount of their annual budget towards the prevention and control of the probable effects of sewer and water pipeline leakage. These issues further exacerbate infrastructure and environmental conditions that support human socioeconomic activities. In recent years, developed countries, such as the United Kingdom, Australia, France, Spain, and the United States of America, have experienced shortage in domestic water supply because of leaking pipe mains [2]. The after effects of these leakages in pipelines cause ground subsidence and sinkholes [3]. These sinkholes result in damage to infrastructure (roads, highways, railways, and underground fluid transportation networks).

A sinkhole refers to a cavity in the ground formed by underground erosion and the depression of the ground surface. In general, there exist two types of sinkholes—natural and human induced. Natural sinkholes are mainly observed in regions with large deposits of salt, limestone, and carbonate rocks. The accurate prediction of the location and time of the occurrence of these sinkholes is rather difficult [4]. Groundwater extraction, construction in adjoining areas, and leakage in underground pipelines are the leading causes of human-induced sinkhole formation in urban areas [5]. Among them, the presence of leakages, bursts, or blockages in sewer, drain, and/or water pipelines are the most frequently reported causes of sinkholes.

The issue of sinkhole creation has witnessed global escalation in recent years owing to ever-increasing urbanization and the continuous construction, development, and expansion of urban areas [6]. A cavity begins to develop as leaked water erodes the soil surrounding pipelines. This reduces the bearing capacity of the soil layer above the cavity, and hence, the ground collapses to form a sinkhole [7]. The size of sinkholes ranges from 2 m deep and 1.5 m wide [5] to a massive scale of up to 15 m deep and 30 m wide [8], as reported in Jeju, South Korea and Southwest Japan, respectively. Human-induced sinkholes have been reported in San Antonio, Texas [9]; Oakwood, Georgia; and Tracer, Colorado [10]. These incidences have reportedly caused considerable economic damage and loss of human lives. As reported in Fraser, USA [10], the abrupt collapse of a 44-year-old sewer pipeline destroyed 22 homes, and the reconstruction of the damaged road and sewer pipelines cost the city administration approximately $70 million. More than 20 sinkholes have been observed in USA alone owing to the failure of underground pipe mains [11]. Figure 1 illustrates the effects of underground pipeline leakage.

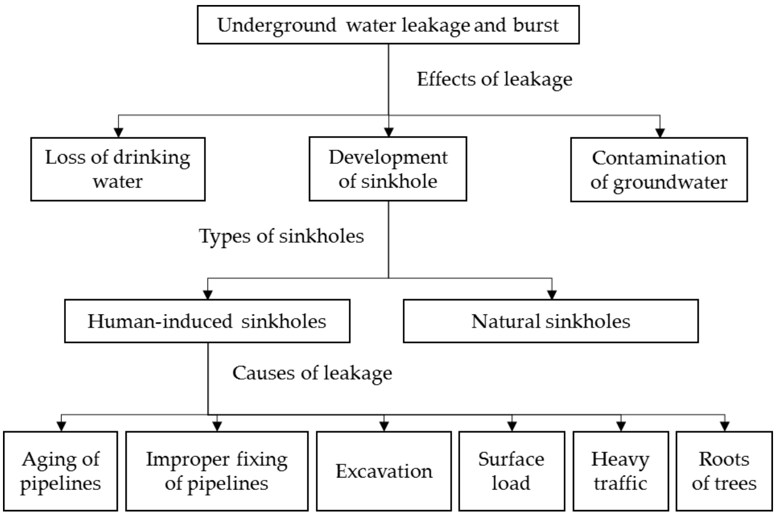

Figure 1. Causes and effects of leakage in underground water systems and sewer pipeline systems.

Various hardware, software, mathematical formulas, and algorithm-based methods have been proposed for monitoring, detecting, and preventing leakages in underground water pipelines and the occurrence of sinkholes. Conventional techniques, such as acoustic-based approaches, have been used for this purpose. These techniques require an expert who scans a suspected area by listening to leak sounds. However, such methods are extremely time consuming and their accuracy highly depends on the skills and experience of personnel [12]. Vibration analysis is another conventional technique utilized to locate leaks in pipelines [13]. However, in conventional vibration and acoustic-based techniques, hydrophones must be placed on both sides of the pipeline section under consideration for leak detection. Such conventional techniques require the exact length of the pipeline to accurately locate a leak. In such cases, the length of the pipeline is measured either by walking with a measurement wheel or by utilizing the recorded data from maps [14]. The lengths obtained using these methods are inappropriate for locating or detecting a leak and result in errors of up to 30% [15]. Various methods have been adopted to monitor and detect sinkholes. Over the years, wireless sensor networking (WSN) systems [16], Internet of things (IoT) [3], and image processing technology using artificial intelligence (AI) have been used for monitoring underground pipeline infrastructures [17]. WSN was first used for pipeline leakage monitoring and detection in 2004 [18]. However, most methods related to WSN, IoT, and image processing mainly focus on sewer and water pipeline monitoring to detect any defects (including leakage) in a more efficient manner in the context of solving the drinking water shortage problem. The after effects (sinkholes) of leakages in sewer and water pipelines have not been discussed and must be examined.

Sinkholes are the most complex civil engineering problems stemming from the interaction of water and the ground. The sinkholes induced by leaking underground pipelines are an important problem that must be extensively investigated. The authors of this paper highlight the major technology-based approaches to obtain a better understanding of the current trends in leakages in underground water and sewer pipelines and their after effects (such as sinkholes). This work aims to find an opportunity for extending existing smart technologies, such as WSN, IoT, and AI, to monitor and detect any signs of sinkholes due to leakages in underground water or sewer pipelines.

The authors aim to demonstrate the exceptional performance of WSN and its application to the detection of sinkholes and to find a suitable solution to optimize the leakage process. Human-induced sinkholes due to leakages in underground pipelines are examined in detail, and the main challenges, issues, and future research areas are elucidated. Furthermore, the authors highlight the WSN-based approaches used to resolve the issue of sinkhole occurrence. The use of smart technology can ensure the future success of underground construction infrastructure industries and create new and clear business objectives. It is important to emphasize that the focus of this study is only on sewer and water pipeline leakages and their after effects.

2. Review Method

2.1. Scope and Objective

This review article concentrated on leakages in sewer and water pipelines and their after effects. It focused on the status of the methods related to the use of WSN to address problems of leakage, burst, and/or blockage monitoring in underground sewer and water pipelines along with the monitoring of the sinkholes caused by these phenomena. The analysis of these methods can provide direction for future research in this area to reduce the occurrence of sinkholes due to leakages. The objective of this review was to provide a comprehensive overview of the state-of-the-art development in leakage and human-induced sinkhole detection and WSN-based monitoring methods.

2.2. Review Execution

This study applied two approaches to comprehensively review the damage caused by sinkholes and leakages in underground water and sewer pipe mains—patent analysis and extensive literature review.

Patent analysis—the patents filed by organizations in different regions worldwide were analyzed using relevant keywords to examine related trends concerning underground sewer and water pipeline leakages and sinkhole creation over the past 18 years. Relevant national and international bodies—Google Patent, United States Patent and Trademark Office, Korean Intellectual Property Rights Information Service (KIRIS), State Intellectual Property Office of the P.R.C, and so on—served as the sources for the patents mentioned in this section, as described in Table 1. Section 3 provides a detailed explanation of this approach.

Literature review—this includes journal articles and conference papers published in regard to the monitoring and detection of leakages in underground water and sewer pipelines and the sinkholes caused by these leakages using WSN systems. Different research article search databases, such as Science Direct, Web of Sciences, and Engineering Village, were used for finding relevant literature published over the past 18 years (2000 to 2018). The reason for reviewing the literature in between 2000 to 2018 was that WSN was first applied to leakage monitoring in 2004 [18]. Section 4 provides a detailed description of WSN-based and IoT-based sewer and water pipeline leakage and sinkhole monitoring and detection methods. Detailed web-of-science analysis was performed to provide statistical data on the reviewed literature. The aforementioned information was collected using keywords such as pipeline leakage, sinkhole, subsidence, sensors, and wireless sensor network.

Table 1. Results of patent search pertaining to sinkhole detection and underground pipeline leakage monitoring.

No.	Patent Database/Office	Total Search Results	Pipeline Leakage Monitoring	Sinkhole Detection	Organization/Country
1	Google Patent Database	251	10	9	Google
2	The United States Patent and Trademark Office	100	8	3	USA
3	Korean Intellectual Property Rights Information Service Database	18	4	2	South Korea
4	State Intellectual Property Office of the P.R.C	15	4	0	China
5	Canadian Intellectual Property Office	15	9	0	Canada
6	World Intellectual Property Organization Office	14	1	0	United Nation
7	Espacenet Patent Search Database	6	2	4	Europe
8	German Patent and Trade Mark Office	6	0	1	Germany
9	Taiwan Patent Search System Database	4	3	0	Taiwan
10	Australian Government Patent Office	2	2	0	Australia
	Total	431	43	19	

3. Patent Analysis

Patent analysis is a unique management tool that deals with a company's technology and strategic management of a product development or service development process [19]. By converting patent data into competitive intelligence, companies can monitor current technological advancements, predict technology trends, and plan for potential competition based on new technologies. This section discusses the patents closely related to the development of leakage detection techniques in underground sewer and water pipelines to prevent potential adverse effects such as drinking water shortage and sinkhole formation.

In this regard, the authors first performed a preliminary search using several keywords related to sinkhole detection and its primary cause—water leakage in sewer pipelines—by utilizing Espacenet Patent Search, which is mainly used in European countries. The authors rapidly realized that different patent-search databases must be used because of the limited number of patents published in this domain. To select patents most relevant to the subject of concern in this study, 10 patent search engines, including official websites, were accessed, as described in Table 1. The database search yielded 431 patents. Approximately 10% (43) of these patents were related to underground pipeline monitoring and leakage detection using WSN, whereas only 4% (19) were related to sinkhole monitoring and detection using WSN.

Table 2 describes the scope of the patents listed in Table 1 in terms of academic and industrial relevance with regard to investigations concerning underground pipeline leakage monitoring and sinkhole formation during 2000 to 2018. Relevant patents have been classified based on the leakage monitoring/detection of underground sewer and water pipelines and sinkhole formation. Out of 43 patents, only 16 patents for pipeline leakage monitoring are cited in Table 2, which are the most relevant to the subject of concern in this study, and 19 patents relevant to sinkhole occurrence are cited. Table 2 further classifies the patents based on whether they belong to the class of safety equipment or method, robotic devices or sensors, or experimental setup or method. As shown in Table 2, until 2010, there were no patents on the implementation of WSN and IoT. However, the application of WSN and IoT has increased over the past two decades. There have been no significant technical advancements in the development of equipment or devices to ensure safety against pipe bursts and sinkhole formation.

Among the patents (16 leakage monitoring and 19 sinkhole detection or monitoring patents) shown in Table 2, the patents most relevant to the subject of concern (patents that used WSN) were selected for further study. Among these filtered patents, six were related to natural sinkhole and water pipeline monitoring and leakage detection methods, while only a single patent was related to human-induced sinkhole detection or monitoring using WSN [39]. The remaining patents mentioned in Table 2 are relevant to leakage monitoring and sinkhole monitoring. However, they do not use a WSN system. The authors created Figure 2 in order to illustrate the concept of different patented methods, which used a WSN system.

Table 2. Patents published concerning underground water and sewer pipeline leakage and sinkhole formation.

Patent Subject Classification	Subcategories	References and Years of Patent Publication							
Leakage monitoring	Safety equipment or method	-	-	[20]	-	-	-	-	[21,22]
	Devices (robots/sensors)	-	-	-	[23,24]	[25,26]	[27,28]	[29–31]	-
	Experimental setup or methods	-	-	-	-	[32]	-	[33]	[34,35]
Sinkhole detection or monitoring	Safety equipment or method	-	-	-	[36]	[37]	-	-	-
	Devices (robots/sensors)	-	-	-	-	[38–40]	[41]	[42–45]	[46]
	Experimental setup or methods	-	-	-	-	[20,47,48]	[49]	[50,51]	[52,53]
Years		2000	2010	2013	2014	2015	2016	2017	2018

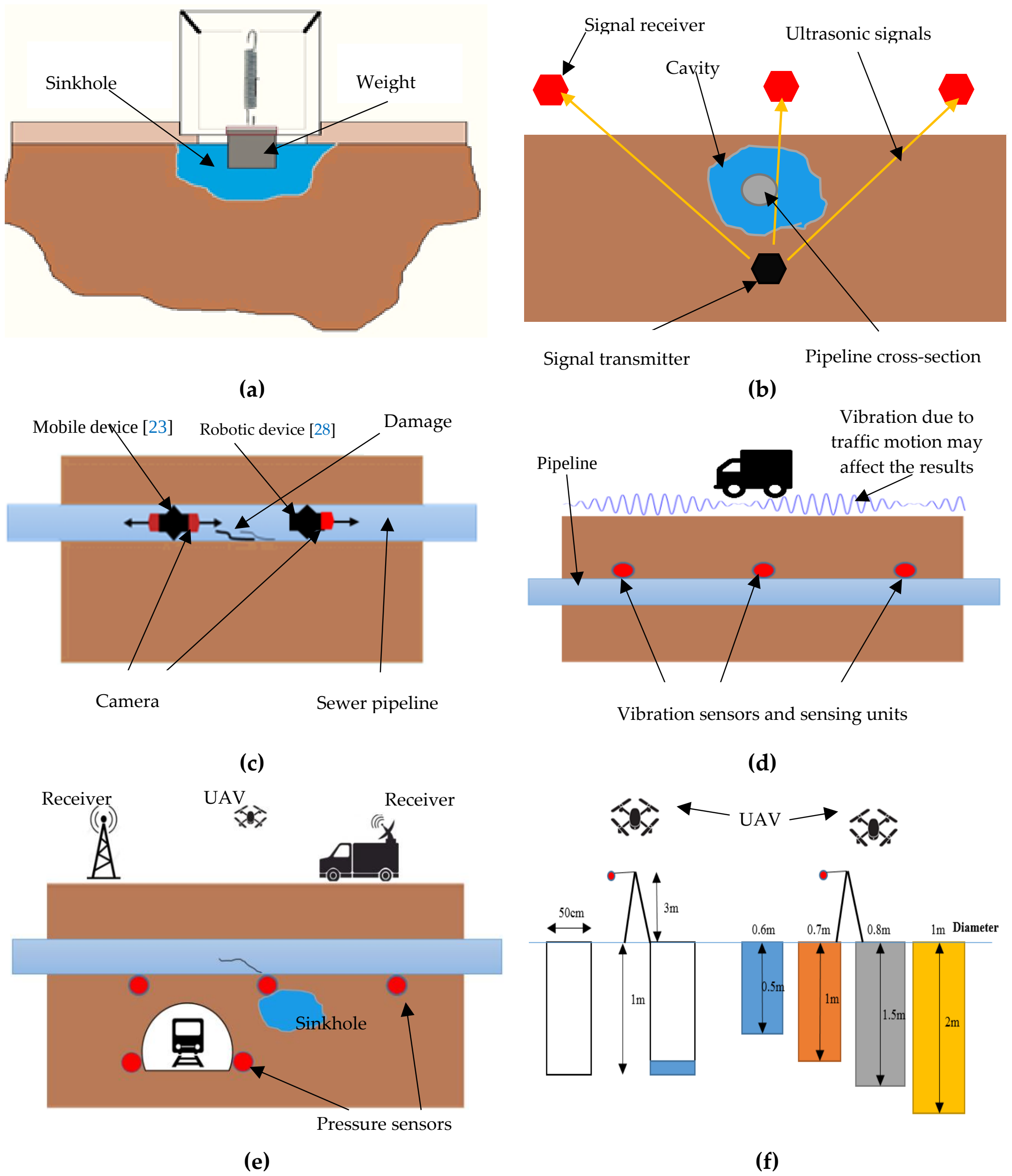

Figure 2. Visual representation of underground water pipeline leakage and sinkhole monitoring methods based on wireless sensor networking (WSN) systems; (**a**) sinkhole detector; (**b**) ultrasonic medium change detection; (**c**) remote pipeline inspection method and mobile-type monitoring device for pipelines; (**d**) pipeline safety and monitoring device; (**e**) sinkhole monitoring system based on pressure sensors; (**f**) simulated sinkhole to develop a neural network learning database for sinkhole detection.

3.1. Patents Related to Sinkhole Detection or Monitoring

First, the patents relevant to sinkhole detection and monitoring are overviewed with their limitations. There are various patents with various operating and functioning techniques such as safety methods to overcome the sudden collapse or sinkhole occurrence [36,37]. Likewise, some patents were invented for sinkhole monitoring via developing experimental setups in laboratories, such methods and experimental setup have been cited in Table 2 [47–53]. However, herein authors just considered patents with applications of WSN. As reported in relevant patents, a device for detecting underground sinkhole formation is partially buried in the ground. A typical sinkhole detector comprises of a cable, a control circuit, and a weight, as depicted in Figure 2a. If a sinkhole is created in the vicinity of the device diameter or under the detector, the device releases the attached weight. This activates a circuit that sends a notification to an administration center [45]. The application of the said device is limited in the sense that it can only detect sinkholes created under the detector or those in the vicinity of its diameter. As the device is of limited size and does not include a WSN system, it cannot be installed for sinkhole detection throughout a pipeline network. Similarly, a sinkhole monitoring system based on pressure sensors has been developed for monitoring human-induced sinkholes. In this method, pressure sensors are placed close to underground utilities such as pipelines and subway tunnels. These pressure sensors comprise of four springs fixed on an axle [39]. When pressure changes in the vicinity of a pressure sensor, the sensor detects the change and wirelessly sends alarm signals to an end user, as depicted in Figure 2e. The signals transmitted underground by the pressure sensors are received by an unmanned aerial vehicle (UAV) or a receiver mounted on a moving vehicle such as a train [39].

A patent describes the application of a neural network learning database for sinkhole detection. This patent is related to the development of a method for creating a small simulated sinkhole cavity characterized by the shape, texture, and complex background of an actual sinkhole. This method utilizes a drone fitted with a thermal imaging camera to detect sinkhole cavities at heights of the order of 10 m [49]. The images captured by the thermal drone camera can be used to construct an image database for the development of a neural network based sinkhole detection model. Figure 2f depicts the schematic of a simulated sinkhole with shapes similar to those of actual sinkholes. A similar device with abilities to detect changes in an underground medium has been developed. This device is used to detect any leakage or deterioration in underground liquid pipelines carrying oil or water [38].

As depicted in Figure 2b, a transmitter device is buried in the middle layer of soil, and several signal receivers are placed above the ground to receive wireless ultrasonic signals emitted from the transmitter. The changes in the paths of these signals while propagating towards the receiver end can be detected by measuring their travel time between the transmitter and receiver. Any difference in travel time indicates a change in the underground medium. A limitation of this device is that ultrasonic signal propagation can be affected by the vibrations and sound effects generated by vehicular traffic on the ground or any other source during practical use.

3.2. Patents Related to Leakage Monitoring

Similar to the above-mentioned devices for sinkhole detection and monitoring, mobile-type monitoring devices for pipeline inspection have been developed to overcome the leakage issues in sewer pipelines [23–31]. Meanwhile, other experimental setups [32–35] and safety equipment [20–22] have been invented for pipeline leakage monitoring. However, these experimental setups and devices did not used the WSN system for pipeline monitoring. Leakage in sewer pipelines that transport wastewater and raw sewage to wastewater treatment plants leads to the contamination of surrounding soil and groundwater and the creation of sinkholes. As depicted in Figure 2c, this problem can be resolved by utilizing modern technology in the form of a remote pipeline-inspection device [28]. This robotic device comprises a camera to capture the images of pipeline interiors, and this data can be transmitted via a communication network for detailed visual inspection, as depicted in Figure 2c. A similar mobile device capable of moving forward and backward with cameras installed on its front and rear sides, as depicted in Figure 2c, can be used to inspect the existence of any leakage, crack, or damage [23] within a pipeline. The said device can be placed inside a pipeline, moved forward up to a fixed point, and made to automatically return to its starting point. The inspection of captured images helps conclude whether the sewer pipe mains has been damaged or not.

These devices [23,28] are currently under use. However, automated image processing and analysis techniques are necessary for replacing human visual inspection, which requires time and effort. With regard to real-time application, the said devices are expensive, time consuming, and require human intervention. Moreover, the devices can only be used to inspect a pipeline section by section, and they cannot inspect the entire pipeline network at once. However, AI-based automation methods are being investigated to facilitate more efficient maintenance compared to visual-inspection methods.

The risk of sinkhole creation has increased because of various ground subsidence phenomena. The method shown in Figure 2d is related to a safety monitoring system for a pipeline, wherein a sensing unit attached to a pipeline network generates position change and vibration signals at regular intervals in accordance with fluid flow inside the pipe to detect leakage and/or rupture in the pipeline. Using the pipe network information already stored in a management server, it is possible to track the position of the damaged parts of a pipeline via the interpretation of received position-change and vibration signals [24]. Sensing units are attached to pipelines using a magnetic outer-bottom portion comprising two subunits—(1) position change sensing unit including acceleration and gyro sensors to generate a position change signal; (2) vibration sensing unit that converts the vibration signals of the installed weight into electrical signals. The device provides the advantage of being able to detect changes in the vibration pattern and position due to the changes in flow velocity when a pipeline is distorted or broken. However, the reliability of the said system may deteriorate because of the transmission of an abnormal signal in the event of strong vibrations caused by construction work or rail and road traffic load.

4. Literature Review

4.1. Web of Science Analysis

A web of science analysis was performed to provide relevant articles and other information such as citations and article categories. From the standpoint of applying the WSN system to monitor and prevent pipeline leakage and sinkhole occurrence, the following different sets of keywords have been used according to trial and error—(1) leakage, pipeline, wireless sensor, and monitoring; (2) leakage, pipeline, and wireless sensor; (3) leakage, water pipeline, and underground; (4) sinkhole and underground; (5) leakage, pipeline, and sinkhole; (6) pipeline, sinkhole, and wireless sensor; and (7) human-induced sinkholes.

Research articles published between 2000 and 2018 with different sets of keywords are summarized in Table 3. It can be observed that a majority of extant studies focused on either leakage monitoring and detection of underground fluid pipelines (numbers marked in red under the water pipeline monitoring category in Table 3) or natural sinkhole monitoring and detection (numbers marked in red under the natural sinkhole category in Table 3). The numbers in orange under the others category in Table 3 indicate the results that are not relevant to the scope of this study (i.e., pipeline corrosion, gas pipelines, underwater pipelines, and aboveground pipeline leakage monitoring). In other instances, search results with different keyword combinations yielded identical results. Only one article was found to be related to sinkhole detection and monitoring due to leakage in underground sewer/water pipelines, as described in Table 3 (the number marked in green).

In accordance with Table 3, after filtering the duplicated articles, 47 articles published in different journals related to sewer/water pipeline and human-made sinkhole monitoring using WSN systems were observed.

Among those 47 articles, majority of the contributions (i.e., 35 articles) were published in journals related to technical domains such as computer science and information systems, telecommunication, electronics, and WSN systems. However, a relatively smaller number of articles (i.e., 12 articles) were published in journals related to application domains such as civil engineering, water resources, soil mechanics, and environmental sciences.

Table 3. Web of science analysis of articles and contributions of different authors related to the field of interest (time span 2000–2018).

Search Trial	Keywords \ Category	Total Articles	Human-Induced Sinkholes	Water and Sewer Pipeline Monitoring	Natural Sinkhole	Others	No. of Citations
①	Leakage, pipeline, wireless sensor, monitoring	22	00	18	N.R [1]	04	146
②	Leakage, pipeline, wireless sensor	23	00	17	N.R [1]	05	154
③	Leakage, water pipeline, underground	17	00	09	N.R [1]	08	185
④	Sinkhole, underground	126	01	02	51	72	956
⑤	Leakage, pipeline, sinkhole	03	00	00	02	01	-
⑥	Pipeline, sinkhole, wireless sensor	00	00	00	00	00	00
⑦	Man-made, sinkholes	23	01	00	13	09	151
	Total	**213**	**01** [2]	**46**	**66**	**99**	**1592**

[1] not related to the intended field of study, [2] total sum of the column is "01" because both articles are duplicate.

The histogram in Figure 3 depicts the above-mentioned 47 articles with the number of publications per year between 2000 and 2018 pertaining to the use of WSN for underground water and sewer pipeline leakage and burst monitoring, and man-made sinkholes.

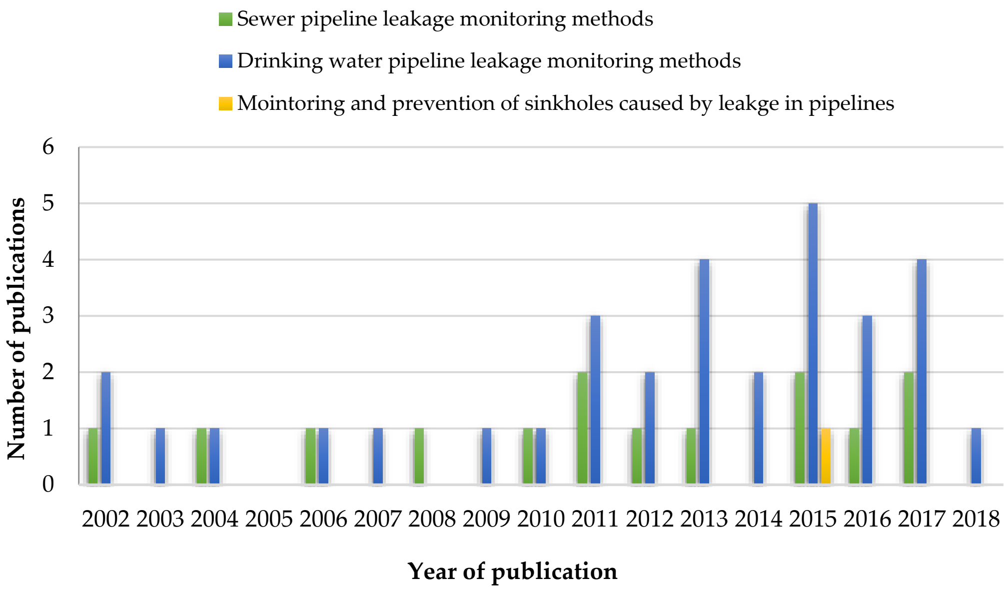

Figure 3. Distribution of number of relevant studies published between 2000 and 2018.

4.2. Overview of Previous Review Articles Related to Underground Water and Sewer Pipeline Monitoring

The WSN system has been tested by monitoring various types of faults in pipelines carrying different substances such as gas, oil, and water [54,55]. Various researchers have reviewed previous methods used for monitoring underground water and sewer pipelines, and they have suggested prospects for improvement. A hybrid method (combining any two different pipeline leakage monitoring methods) to form a new and more reliable solution was suggested in articles [56] and [57]. According to [58,59], there are two critical issues that need improvement in terms of development of a preferable underground WSN system—(1) efficiency of network-communication range and (2) energy efficiency of WSN.

Adedeji et al. [60], in their review article, discussed and suggested the importance of sensor-deployment strategy for reliable and scalable data propagation in the soil channel. Similarly, different methods for underground pipeline-leakage monitoring were compared in [61]. Acoustic reflectometry was found to be the most reliable method among all the reviewed methods, because it is applicable to various linear pipeline layouts (i.e., straight, short, long, and zigzag) while being one of the most energy efficient and reliable methods. Table 4 lists extant review articles published on monitoring underground water and sewer pipeline leakage using WSN-based systems in the reverse chronological order. The listed articles also discuss suggestions for future research and challenges encountered during each review.

Table 4. Summary of future research suggestions pertaining to underground water and sewer pipeline leakage and sinkhole monitoring using WSN-based systems, as discussed in extant review articles.

Article	Future Research Suggestions	Research Field	Publication Year
Abdelhafidh et al. [56]	Combination of several leak detection methods to form one hybrid system for better results.	Computer Sciences	2018
Adedeji et al. [60]	Sensors deployment strategies in WSN nodes need to be considered.	Electrical Engineering	2017
Datta et al. [61]	Acoustic reflectometry is most suitable for leakage and blockage in underground pipelines.	Mechanical Engineering	2016
Sheltami et al. [57]	Hybrids of different WSN-based pipeline monitoring techniques to enhance the detection and localization of leakage.	Computer Sciences	2016
Obeid et al. [62]	Integrated energy-aware system on chip solution for non-invasive pipeline monitoring.	Electronics and Communication	2016
BenSaleh et al. [58]	Developing energy-efficient nodes with adequate sleep and wake-up mechanisms.	Electronics and Communication	2015
BenSaleh et al. [63]	Develop a robust and reliable system, which is cost-effective, scalable, and customizable in future.	Electronics and Communication	2013
Tariq et al. [59]	Improvement in the communication radius efficiently.	Computer Sciences	2013

From Table 4, it can be concluded that all suggestions for future research are related to the fields of computer science, electrical, electronics, and telecommunication sectors. Therefore, it can be considered that all researchers, in their respective review articles, aimed to present the challenges encountered in the field of WSN, sensor-deployment strategies, and communication radius of the system. However, in the fields of soil mechanics, civil infrastructure, and geology, the after effects of leakage on the surrounding soil must be considered. As mentioned earlier, leakage can lead to soil erosion and ultimately results in sinkholes.

4.3. Architecture of Underground WSN Systems for Pipelines

Different networks and communication protocols have been used to monitor the underground and aboveground water pipelines for the transmission and propagation of sensor data to end users. A WSN consists of various units that work together to gather desired data in a specific environment where communication can be established over a wireless channel, including sensing, computing, and communication devices [64,65]. There are three tiers—(1) sensor tier; (2) master-node tier; and (3) end user—in any underground WSN system for pipelines, as depicted in Figure 4. In the sensor tier, sensors are placed along the pipeline network to wirelessly transmit assigned data to the master node, which subsequently transmits data to the end user(s). The main distinction between underground and terrestrial WSN systems is the communication medium (soil or air) [66].

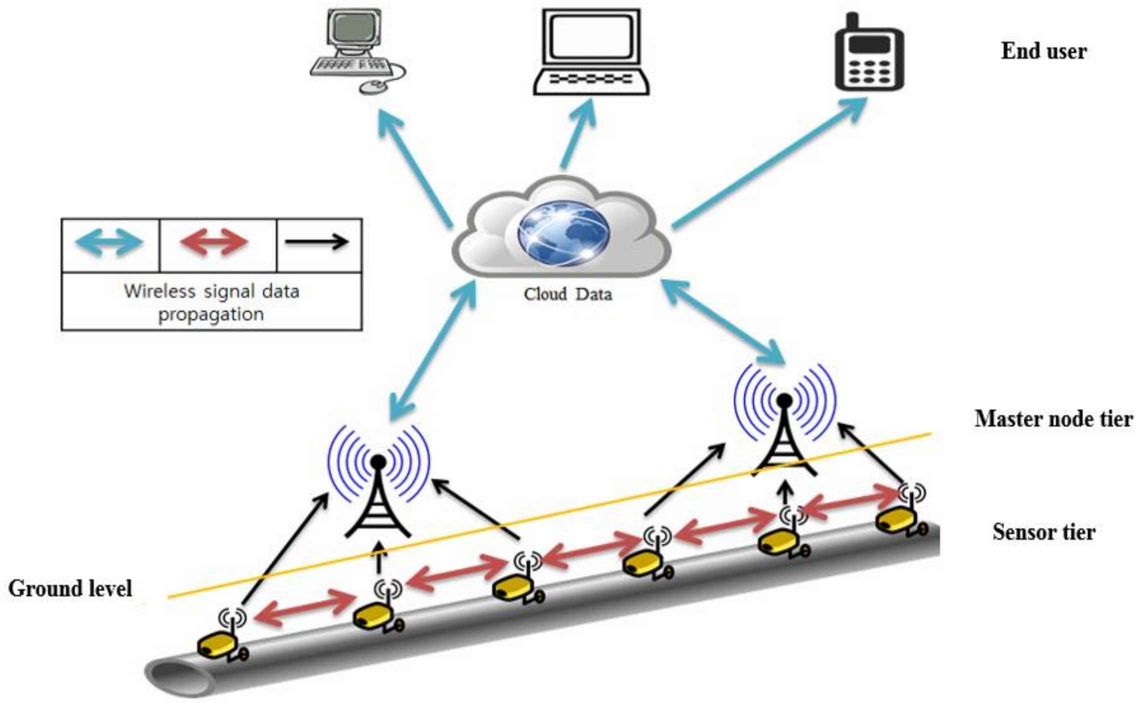

Figure 4. Typical WSN architecture for underground water pipeline monitoring.

Many wireless sensor communication protocols and interfaces, such as Wi-Fi, ZigBee, LoRa, and Bluetooth, have been used to overcome multiple transducer connectivity problems [67,68]. Table 5 explains the characteristics of commonly used communication protocols along with their properties such as speed, range, frequency, and limitations. Bluetooth is applicable for communication over a short range of 1–100 m with better data transmission speed in comparison to ZigBee and GPRS. Certain communication protocols such as GPRS and 3G possess low data transfer speed but their range is up to 10 km. Some communication protocols such as 5G, 4G, 3G, and LTE provide a somewhat longer communication range with high data-transmission speed, whilst requiring a large spectrum fee [69,70]. It is, therefore, essential to select a communication protocol based on the end application and availability of required resources to achieve desired results of cost-effectiveness, reliability, and low power consumption. The communication protocols listed in Table 5 are in order of increasing range of different protocols.

Table 5. Communication protocols and their properties [69,70].

Communication Protocol	Speed	Range	Frequency	Limitations
Bluetooth	3 Mbps	1–100 m	2.4–2.48 GHz	Short range
Wi-Fi	300 Mbps	100 m	2.4–5.4 GHz	Short range
ZigBee	250 Kbps	75 m	2.4 GHz	Low data rate and short range
Z-Wave	40 Mbps	30 m	868.42–908.42 GHz	Low data rate and short range
GPRS	Up to 170 Kbps	1–10 km	900–1800 MHz	Low data rate
3G	384 Kbps-2 Mbps	1–10 km	2.5, 3.5, 5.8 GHz	Costly spectrum fee
WiMAX	Up to 75 Mbps	10–50 km	1–30 MHz	Not widespread

4.4. Water Pipeline Leakage Monitoring Methods Based on WSN System

The loss of water is one of the most critical issues, particularly in urban localities. In an urban framework, the occurrence of any severe pipeline leakage issue such as water supply interruption and traffic flow interruption may intensify, thereby resulting in an increase in maintenance costs. Therefore, the implementation of a robust, reliable, and energy-efficient WSN-based system is imperative to overcome water loss issues and after effects of leakage [71]. Ng et al. [72] proposed a vibration sensor-based sound variation detection device that records suspicious water leakage sounds and compares them with normal pipeline sounds, thereby identifying the symptoms of water leakage. The device was used on two types of pipelines—metal and PVC—but not concrete ones. The said device has a disadvantage, that is it only functions properly when installed near a leak point, and it is immensely difficult to predict the exact location of leakage. It is also not clear to judge the utility of the device when on concrete pipes.

Four things—cost efficiency, reliability, power consumption, and sensor placement across the pipeline network—must be considered regarding monitoring underground sewer/water networks and sinkholes using WSN. Cattani et al. [73] proposed a method called ADIGE based on the long-range LoRa WSN technology to reduce the number of gateways uploading data gathered from wireless sensors. The proposed ADIGE system comprised two parts—(1) sensing, controlling, and collection of data; and (2) data management, including data fusion and analysis—as depicted in Figure 5a. This method was designed to achieve high reliability and energy efficiency along with wider coverage of water pipeline monitoring using a large number of low-cost sensors for collecting more real-time information at multiple locations instead of using lesser numbers of expensive sensors installed at fewer locations. However, using the WSN system to accurately identify leakage locations inside a long-running water pipeline and the effects caused by leakage remains a major challenge for researchers.

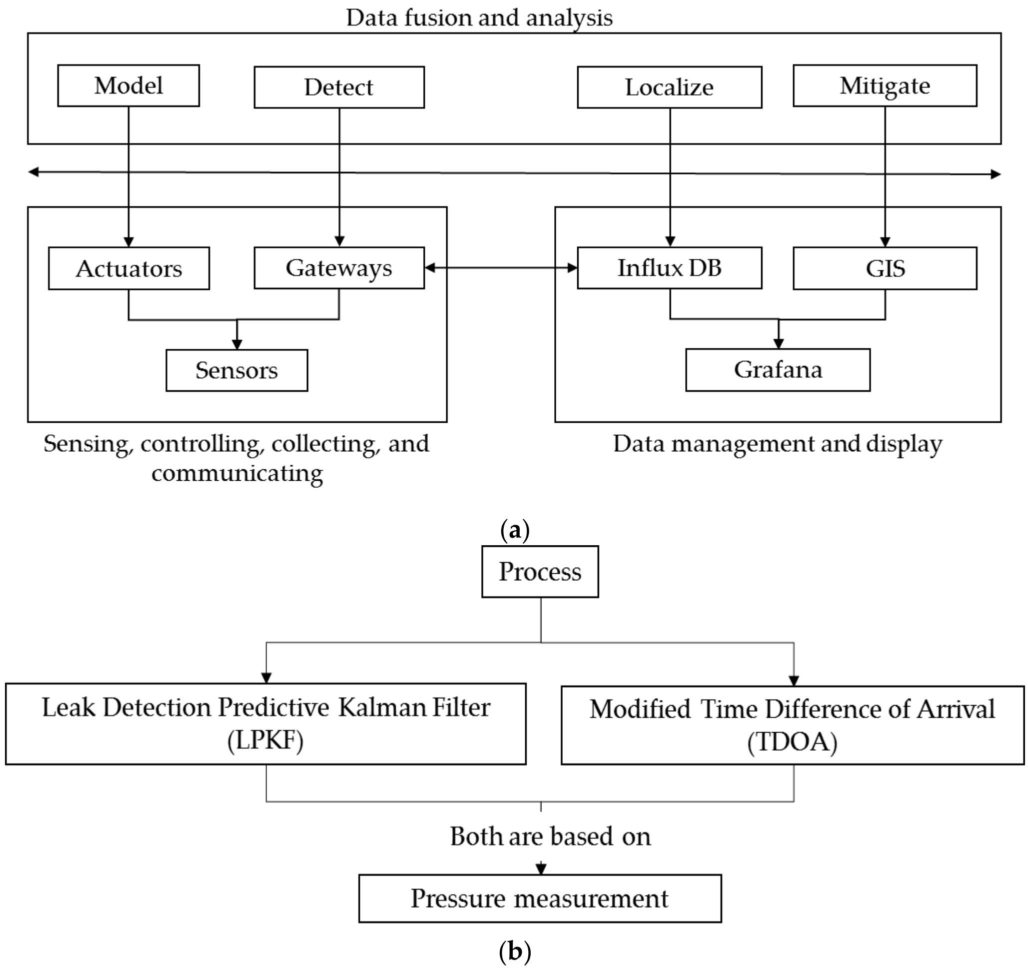

Figure 5. Leakage monitoring methods using different combinations and algorithms for leak detection and localization: (**a**) System combination of method based on the long-range LoRa WSN technology; (**b**) different types of methods and algorithms used for leak detection and localization.

Karray et al. [74] also proposed a method to identify leakage locations within a pipeline network. This method involved the use of a combination of leakage detection algorithms, localization algorithms, and system-on-chip (SoC) architecture. This solution was based on two methods, as described in Figure 5b. Instead of using multiple algorithms at once to compromise battery life, the author preferred using single algorithm—the Kalman Filter (KF)—to conserve energy. The method used for this purpose was referred to as energy-aware reconfigurable sensor node for water pipeline monitoring (EARNPIPE). A plastic pipeline capable of supporting pressures of up to 25 bar and 1000 m^3 volume of water was used to supply water using 1 hp power supplied by the laboratory test bed motor. A force-resistive sensor (FSR) was used to measure the pressure within the pipelines. The said method was proposed for use in long-distance pipelines installed on the ground but was not suitable for use with underground pipelines.

Sun et al. in [75] suggested a new solution for water pipeline monitoring, leakage, and burst detection. Real-time leakage and burst detection were set as the primary objectives of this method. Considering the propagation of sensor signal data in soil, a WSN system based on magnetic induction (MI) was proposed. The sensors were distributed into two layers—(1) the hub layer and (2) in-soil sensor layer. In the hub layer, pressure and acoustic sensors were deployed at checkpoints and pump stations inside pipelines to measure pressure and vibration changes caused by leakage, as depicted in Figure 6. After measuring the values of pressure and vibration, data were wirelessly sent to the administration center using MI channels. Whereas in the in-soil layer, sensors were deployed along the pipeline to measure different soil parameters such as temperature and humidity. This was accomplished by rolling MI relay coils around the pipes. Beyond the system architecture and framework presented in this article, more work regarding evaluating the system performance is required to be performed by deploying MI-based WSN for underground pipeline monitoring (MISE-PIPE) in real-life applications.

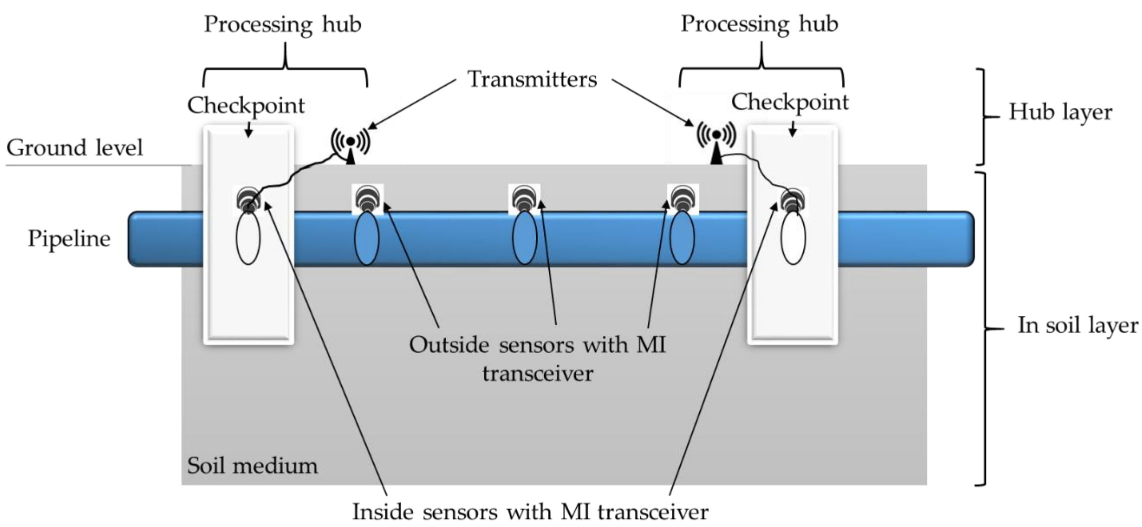

Figure 6. System architecture of magnetic induction (MI)-based WSN for underground pipeline monitoring (MISE-PIPE) [75].

4.5. Sewer Pipeline Leakage Monitoring Methods Based on WSN Systems

Leakage in sewer pipelines needs to be considered as a potential source of underground cavity creation and sinkholes in urban areas. According to Kuwano et al. [76], the sewer pipe mains buried underground for over 25 years demonstrate a remarkable increase in cracks and defects. Researchers and scientists have contributed toward the development of means to address issues related to cracking, leakage, and bursting of sewer pipelines. Kim et al. [77] proposed a novel RFID-based autonomous mobile device monitoring system for pipelines, called RAMP. The mobile robotic device comprising sensors (visual-, chemical-, pressure-, and SONAR-sensing) was capable of moving inside the pipelines along the direction of fluid flow whilst monitoring the presence of any defect on its way and localizing the same. The primary function of the robotic agent was pipeline inspection. However, the system requires a structure with improved fluid resistance and enhanced mobility of the robotic agent because at present its usage is only limited to inside straight pipelines. Additionally, to achieve better results, energy efficiency and sensor power must be improved. Such methods are equally applicable to water, sewer, and pipelines [77].

Similarly, PIPENET is a system proposed for pipelines with large diameters, such as sewer and drainage pipelines, and comprises a WSN-based system for underground pipeline leakage detection and localization [78]. For real-time monitoring, the system was deployed in collaboration with Boston Water and Sewer Communication (BWSC), USA. Their deployment primarily focused on two critical applications—(1) sewer collector's water level monitoring and (2) hydraulic and water quality monitoring [79]. The method aimed to detect and localize the presence of any leakage or burst within the pipeline by collecting the hydraulic and vibration data at a high sampling rate using different sensing parameters—flow, pH, vibration, and pressure—and data collection was performed for an extended period of over 22 months in the city of Boston, USA. The experiment was performed both inside a laboratory and in the field to compare the experimental results and develop an algorithm for leakage detection and localization. Some limitations of this method include false alarms and low energy efficiency. Considering sewer pipelines, robot-sensing devices have been preferred to monitor the condition and performance of pipelines [77].

Most robots used for the inspection of sewer pipelines moved along one direction (straight). In contrast, KANTARO was an innovative, fast, and robust sensing device intended for use in sewer-pipeline inspection. The device could move in a straight path as well as bend around the curves. For this, a particular patented mechanism called the "Sewer Inspection Robot (nSIR) Mechanism" was developed [80]. KANTARO was equipped with a fisheye camera mounted to detect any damage or blockage within the sewer pipeline network. It could only fit in pipelines with internal diameters in the range of 200–300 mm and included lithium-polymer batteries for power supply to motors, sensors, computer systems, and underground wireless communication modules.

4.6. Pipeline Leakage Monitoring Methods Based on Computer Vision and Image Processing

Other such approach involved the use of closed-circuit television (CCTV) image processing by concerned researchers for the detection of defects and damages in sewer pipelines. Manual interpretation of images and videos has previously been used, and those methods were observed to be more time consuming, labor intensive, and the results obtained were deemed to be less reliable and possibly inaccurate. In contrast, automated defect detection methods have been proposed by researchers using artificial intelligence (AI) and CCTV image and video processing techniques, such as the deep learning technique called the faster region based convolutional neural network (faster R-CNN) [81]. The faster R-CNN model has been demonstrated to detect defects in sewer pipelines much faster with higher accuracy.

However, the faster R-CNN approach only works on static images. Similarly, the authors in [17] used an automated approach to detect cracks, deformations, joint displacements, and settled deposits in sewer pipelines. Their approach was based on image processing and mathematical formulations to analyze the output obtained from CCTV images. To validate the performance of the proposed method, the authors in [17] constructed a confusion matrix. The results observed for the accuracy of crack, displaced-joint, and settled-deposit detection were found to 74%, 65%, and 54%, respectively, which could be improved by increasing the number of images captured. A drawback of the proposed methodology was that the method relied heavily on the expertise and experience of operators. From the literature overviewed in earlier sections it is evident that over time, technologies have developed from the visual inspection of sewer/water pipelines to the application of wired sensors, wireless sensors, IoT, big data, and AI technologies, as illustrated in Figure 7.

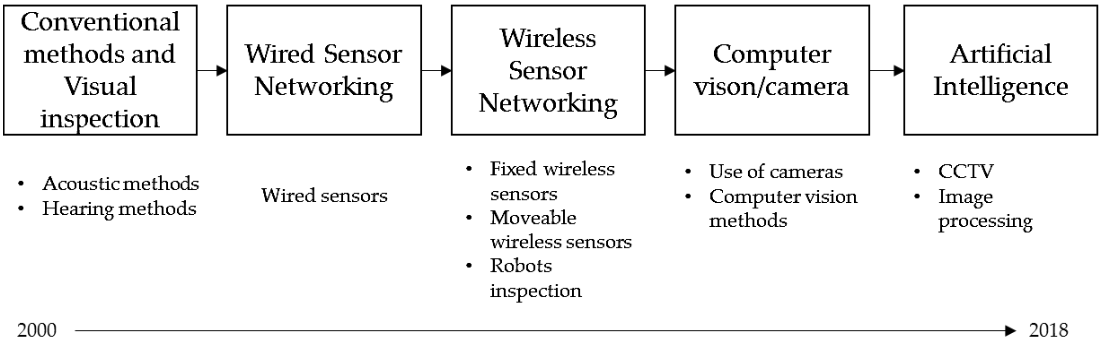

Figure 7. Illustration of technological developments in underground pipeline network inspection methods over time.

Using WSN-based systems, previously discussed sewer and water pipeline surveillance models (Sections 4.4 and 4.5) are summarized in Table 6. This table provides a detailed perspective of WSN-based sewer and water pipeline leakage monitoring methods in terms of the protocols used for wireless communication between the transmitter and receiver, type of wireless sensors used (non-invasive or invasive sensors, static or mobile sensors, etc.), field of application, and water or sewer pipeline network. Table 6 makes it easier to determine the most feasible method to monitor water and/or sewer pipelines under certain conditions. Meanwhile, it also helps to select the most feasible methods, which can be further modified for the application of sinkhole due to leakage. For example, Sun et al. [75] used sensors both inside and outside the pipelines to detect various factors related to leakage. In such methods, more soil property measuring sensors can be added to further collect data related to the factors (soil moisture, density, temperature, overburden, and porosity, among others) that contribute to the occurrence of sinkholes.

Table 6. Comparison of various methods for leakage detection in water and sewer pipelines.

Method (Ref.)	Communication Protocol	Types of Sensors	NIS [1]	IS [2]	Mobility	Application Field
[82]	-	-		•	Mobile	Sewer pipeline
[72]	3G	Acoustic sensors.	•		Static	Drinking water pipeline (PVC and steel pipes)
[83]	GSM	Ultrasonic and water sensors.	•		Static	Leak in home pipelines and the water level of the tank.
[73]	LoRa	Adige sensors.	•		Static	Drinking water pipeline
[74]	Bluetooth	Pressure sensors (FSR).	•		Mobile	Drinking water pipeline
[75]	Magnetic induction	Soil property, pressure, and acoustic sensors.	•	•	Static	Drinking water pipeline
[17]	3G	Temperature, pressure, flow rate, and hydrophone.		•	Mobile	Drinking water pipeline
[18]	RF signals	Acoustic sensors.			Static	Drinking water pipeline
[77]	RFID	Vibration sensors and robot agents.	•		Static	Drinking water and sewer pipeline
[78]	Bluetooth	Vibration, flow rate, and pressure sensors.	•		Static	Drinking water pipeline
[80]	RF signals	IR, tilt and image sensors, and laser scanner.		•	Mobile	Sewer pipeline
[3]	ZigBee	Pressure, piezoelectric sensor, gyroscope, and accelerometer.	•		Static	Drinking water pipeline
[84]	CAN (wired), X stream, X Bee, and Wi-Fi (wireless)	Vibration sensors and accelerometer.	•		Static	Drinking water pipeline
[85]	RF signals	Hydrophone.		•	Mobile	Drinking water pipeline
[86]	X stream, X Bee, and Wi-Fi	Accelerometer.	•		Static	Drinking water pipeline
[87]	RF signals	FSR sensors.	•		Static	Drinking water pipeline
[88]	ZigBee	Vibration sensors.	•		Static	Drinking water pipeline
[89]	-	-	•		Mobile	Sewer pipeline
[90]	WSN	Pressure and flow rate sensors.	•		Static	Sewer pipeline
[91]	-	-		•	Mobile	Oil and gas
[92]	-	-	•	•	Mobile and Static	Any pipelines

[1] NIS: Non-invasive sensors (sensors placed outside a pipeline), [2] IS: Invasive sensors (sensors placed inside a pipeline).

4.7. Sinkhole Monitoring and Detection Methods

A record of the past 60 years of Gauteng, South Africa, reports the occurrence of more than 3000 sinkholes, including natural and human-induced ones [93]. The Maryland geological survey reported a total of 139 sinkhole occurrences, 51 of which occurred naturally, while the remainder were the human-induced type [94]. According to the British Geological Survey (BGS) (a British government institute), 10% of all sinkholes occur as a result of leakage in underground pipelines [82]. As discussed in previous sections (Sections 4.4–4.6), various methods are adopted for leakage monitoring. However, sinkholes due to leakage require proper concentration as they result in considerable damage. According to the US Geological Survey, nearly $300 million per year is spent on the reconstruction of, and compensation for, damage caused by sinkholes to the infrastructure [95]. The frequency of sinkhole occurrence has increased considerably in South Korea, since 2010, mainly because of underground construction in urban areas. An account of the total occurrence of sinkholes in Seoul, South Korea, between January and July 2014 reported that ruptured sewer pipelines resulted in approximately 85% of all man-made sinkholes, 18% were triggered by excavation during construction activities, and the remaining 3% were caused by leakage in freshwater pipelines [96].

Sinkholes occurs on roads, highways, and railways owing to the infiltration of leaking underground pipelines or rainwater. These cavities can be detected beneath the surfaces using different monitoring and detection methods. Although many sinkhole detection methods have been developed, it is still difficult to predict the formation of sinkholes. There are alternative methods to predict when and where sinkholes will form. Researchers have drawn maps for sinkhole-prone regions that predict risk based on the ground composition or other local sinkholes; however, this still does not provide a definite answer.

4.7.1. Sinkhole Monitoring Methods Using Image Processing and Radar

Many researchers have contributed toward the prediction of the occurrence of natural sinkholes via the use of diverse technologies, such as the trenching method along with ground penetration radar (GPR), electrical resistivity tomography (ERT), high-precision leveling [97], Brillouin optical fiber sensor [98], high-precision differential leveling [99], laser imaging detection and ranging (LIDAR), and interferometric synthetic aperture radar (InSAR) [100]. The combined use of the geographic information system (GIS) and analytical hierarchical process (AHP) has previously been proposed to identify hazard zones in Kuala Lumpur and Am pang Jaya of Malaysia that are susceptible to the occurrence of natural sinkholes on the basis of five criteria—lithology, groundwater level decline, soil types, land use, and proximity to groundwater wells [4]. However, the human-made (owing to leakage) requires proper concentration.

As in the UK, the British Geological Survey used digital map data for geohazard monitoring in urban areas. This digital map data can be accessed from GIS [101]. High-resolution ground-based InSAR (GB-InSAR) and LiDAR are methods available for sinkhole monitoring. These technologies use GIS data for sinkhole mapping and are particularly effective for sinkhole tracking [100]. However, it is challenging to discern sinkholes or subsurface features based on GIS data or satellite data [102]. Soil erosion gradually leads to collapse, and the application of GB-InSAR, LiDAR, scanning, and photogrammetry methods have to scan and analyze different areas continuously to observe the changes over time, which can be expensive and time-consuming. Therefore, the current practices in urban areas for monitoring and detection of the sinkhole are limited.

Similarly, in some developed countries, ground penetration radar (GPR) is currently used for sinkhole monitoring and detection, especially in urban areas. The results of a GPR rely on the reflection of a high frequency (25–1000 MHz) electromagnetic (EM) pulse from subsurface contacts and other anomalies such as boulders and cavities. [103]. GPR uses radar pulsations to predict the changes in the subsurface. This method uses EM radiation of the radio spectrum and detects the reflected signals from the subsurface structures [104]. However, there are limitations associated with GPR, as noise effects the magnetic techniques, and the presence of clayey soils affects the transmission of EM signals from GPR [105]. Previously, the application of GPR was excluded from the investigation in Nigeria owing to the presence of clay [106].

Other methods include geomorphological mapping, borehole drilling, and air photo interpretation. Table 7 lists the methods currently available to address challenges and obtain solutions for sinkholes; their advantages and limitations are also discussed.

Table 7. Sinkhole monitoring and detection techniques.

Sinkhole Detection and Monitoring Techniques	Positive Aspects	Gaps	References
GIS with digital map data	Allows for spatial analysis, assessed specific problems using multi-criteria approach.	Scale-dependent, needs geo referencing, software, and manpower expertise.	[107]
GPR and InSAR	Subsurface detection and mapping.	Equipment (some expensive/specialist) and expertise required.	[108–110]
Leaser image detection and ranging system (LiDAR)	Provides high-resolution images for monitoring of sinkholes or subsidence.	Detection of subsurface changes are not possible; only limited to surface detection.	[111,112]
Electric resistivity tomography (ETR)	Subsurface detection and mapping.	Expensive equipment and expertise required to operate.	[109,110,113]
Drones (UAV) and photogrammetry	Spatio-temporal analysis is possible.	Limited to surface analysis and dependent on availability of drones and photogrammetry equipment.	[114–116]
WSN	Can be integrated with geological information; can integrate geophysical information.	Limited to surface-based assessment.	[3,117,118]

4.7.2. Human-Induced Sinkhole Monitoring Methods Using WSN

Soil strata and profile vary from for different regions and are characterized based on the unique geomorphological and hydrological conditions, and pipelines are not limited to areas with specific geology. If we consider the subsurface of any urban area, miles of water and sewer pipelines are passing through different soil profiles. Therefore, the effect of water leakage from sewer or water pipelines will be different for different subsurface soil strata.

A leakage in the sewer or water pipeline results in the change in underground soil and other various problems mentioned above. Over the past few years, numerous cases of sinkhole creation owing to the rapid deterioration of underground sewer and water pipelines have been reported. To overcome this issue, researchers have developed sensor-based pipe safety units to detect leakage by analyzing water leaks and pipeline behavior. Pipeline data are collected by the use of smart sensors and WSN [3]. However, the system is still being developed, and the primary purpose of the program is to develop a sinkhole risk index (SRI) via the real-time monitoring of underground construction activities. This is an individual research endeavor aimed at the prevention of sinkhole creation due to leakages or ruptures in underground sewer pipelines owing to human interference. In the said study, experiments were conducted on a buried pipeline, exposed pipeline, exposed acrylic pipeline, and test-object pipe. During the experiments, the concerned researchers used cables for the connection between sensors.

However, previously, researchers have suggested several methods for the study of the mechanism of natural sinkholes by considering different factors that influence the occurrence of natural sinkholes. Therefore, different numerical, mathematical, and experimental models have been developed. Each researcher in their experimental model considered different sinkhole mitigating factors and soil types to understand the mechanism.

Researchers considered sea side soil (mudflat, sea clay) as a soil type, and subsurface void growth, ground water level, salt dissolution, and overburden pressure as the factors responsible for sinkhole or subsidence in their experiments [119,120] as the researchers aimed to understand the mechanism of sinkhole along the seaside. Therefore, this sinkhole mechanism cannot be true for other cases, as other soil types need to be considered (clay, sand, bedrock, carbonates, etc.) and other sinkhole mitigating factors (size of cavity, subsurface soil properties, aquifer, etc.). Similarly, Tao et al. [121] also performed a numerical simulation to understand the mechanism of natural sinkholes owing to changes in ground water table. Sand and clay were used as the soil profiles for the sinkhole model. However, similar to previous contributions, this study was just limited to understanding the natural sinkholes mechanism. In addition, it must be improved to increase the simulation capabilities.

5. Discussion and Conclusions

Numerous conventional techniques have been used over the years for the accurate detection of water and sewer pipeline leakage and prevention of sinkhole creation. However, there are a few limitations in the execution of conventional techniques such as high cost, need for large workforce and experts, long execution times, and unreliable results. Over the years, conventional methods have been replaced by methods based on IoT, WSN, smart sensors, and AI; these methods are more manageable and reliable.

This article focuses on research contributions regarding the use of WSN for water and sewer pipeline leakage and sinkhole monitoring and detection, thereby providing methods to prevent the creation of sinkholes in urban areas. The proposed review was performed following a two-pronged methodology—patent analysis and literature review of methods used for monitoring underground pipeline leakage and sinkhole creation using WSN-based systems. Both patent analysis and literature review demonstrated a lack of research on the prevention or monitoring of sinkhole creation caused by leakage in water and/or sewer pipelines.

The development of modern technology has led to the development of improved water and sewer leakage monitoring systems. However, modern, technology-based monitoring systems require efficient communication technologies such as 5 G in combination with WSN to create an advanced infrastructure such as underground fluid transportation networks. Over the last decade, new wireless communication networks have been developed to serve a range of new applications and deployment scenarios. Similarly, smart cities are being developed, where WSN and 5 G are considered to be one of the key enabling technologies that will provide smart solutions to smart cities to improve the overall quality of life [122].

5.1. Review Findings

The results of a preliminary search of patent databases demonstrate that a majority of patents published in the past 18 years were related to overcoming leakage problems associated with water and sewer pipelines. However, they lack in terms of suggesting measures to counter the after effects—sinkholes and ground subsidence—of leaked water and sewer pipelines. Additionally, existing patents for sinkhole monitoring and detection face several limitations. For instance, the "sinkhole detector" can only detect sinkholes near the installed device [45]. Similarly, the patent named "device for detecting changes in underground medium" explored the use of ultrasonic sensors; however, the propagation of ultrasonic signals can be easily affected by the soil medium, traffic-induced vibrations, and sound effects generated by different means of transportations or other sources.

Similarly, the literature review conducted in this study revealed that majority of researchers are concerned with overcoming the water losses caused by leakages in sewer and water pipelines. Particularly, a burst or leak of a sewer pipeline can endanger human lives as well as damage nearby infrastructures such as railways and highways; this is because most cases of human-induced sinkholes and ground subsidence are caused by leakages in sewer pipelines [123]. Compared to naturally occurring sinkholes, human-induced sinkholes incur less damage to infrastructures and human lives and this is why they have not been considered a significant issue by researchers in the past. However, over the last few years, sinkholes caused by leakage in water and sewer pipelines have become a severe problem across the world. Natural, as well as human-induced, sinkholes cannot be directly detected, and in this regard, the development of SRI or a sinkhole risk model is considered likely to play the role of a bridge between leaky pipelines and sinkhole detection [3].

However, no prominent studies have yet been found concerning the monitoring, detection, prevention, and localization of human-induced sinkholes. There exist many factors—soil type, topography of the area under consideration for sinkhole evaluation, history of sinkhole occurrence, recharge-area category, thickness and depth of underground cavity, groundwater table, and public safety—that need to be considered during sinkhole risk or risk index evaluation [124]. Similarly, other factors such as temperature, moisture content, and porous water pressure of soil, which may also change owing to a leakage or rupture in underground water or sewer pipelines, require proper attention.

5.2. Future Research Directions

After a critical analysis of various methodologies used by researchers previously in the domain of water and sewer pipeline leakage and sinkhole induction, the authors believe that there are certain major challenges that must be addressed on priority. Sinkhole formation, or collapse of the ground caused by a rupture or leakage in underground sewer and water pipeline, requires considerable attention. Similarly, there exists an urgent need for the development of a human-induced SRI to determine the magnitude of the occurrence of sinkholes induced by underground sewer and water pipeline leakage.

The authors advocate toward utilizing a set of technological tools to assess the occurrence of sinkholes by prioritizing the critical factors associated with them. State-of-the-art technologies such as AI and WSN can be used in combination to monitor and access the geographical changes and the locations that are at a higher risk of sinkhole formation owing to leaked underground pipelines. Image processing techniques based on AI platforms can be implemented to monitor disruptions at both the ground surface level and the underground pipeline level. Combining these techniques with WSN, which uses sensors to determine soil properties such as moisture, density, porosity, pH, temperature, and bearing capacity, can help to gain a better understanding of the processes at this geographical location.

As WSN was previously used to analyze the physical properties (vibration, flow rate, sound, and so on) of pipelines and their flow in order to monitor leakage, it did not concentrate on the properties of the soil profile, which can change after the interaction of soil with water leaked from the sewer/water pipelines. Thus, the systematic approach proposed in this paper can pave the path for future research in this area. In the future, such technological tools can be used in smart cities to overcome the issues of pipeline leakage and sinkhole formation, where radio technologies such as 5 G enables smart city networks to support interconnected infrastructure elements and to manage big data from existing smart infrastructures [122].

An evaluation of previous research publications in this area clearly shows that a majority of the methods used are based on laboratory experiments and the findings and proposals appear to be difficult for practical application. Therefore, to achieve significant improvement, we suggest implementing collaborative exercises between research institutes and water supply agencies.

5.3. Conclusions

Based on the analysis reported in this study, it can be concluded that the key focus of research in existing studies has been concerned with (1) the use and enhancement of wireless sensor networking systems; (2) types and quality of sensors; and (3) improvement of hardware and software systems adopted for underground water and sewer pipeline monitoring. Although soil properties, such as bearing capacity, water content, soil density, air voids, pH level, ground subsidence, and others, change owing to pipeline leakage, these have seldom been considered in previous investigations. Nonetheless, these parameters are critical with regard to triggering sinkhole formation and ground subsidence owing to leakage in water and sewer pipelines. This article presents a state-of-the-art review of different methods for monitoring sinkhole and underground water and sewer pipeline leakage and their effects whilst considering the use of applications based on IoT and WSN systems over the past two decades.

This review would be of interest to researchers intending to work in this area as it serves as a platform to direct future studies whilst accounting for challenges likely to be encountered during the same.

Author Contributions: H.A. and J.C. wrote the original draft supervised by J.C.

Funding: This work was supported and funded by the Basic Science Research Program through the National Research Foundation of Korea (NRF) and funded by the Ministry of Education (2016R1A6A1A03012812 and 2017R1D1A1B03036200).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Karoui, T.; Jeong, S.Y.; Jeong, Y.H.; Kim, D.S.; Karoui, T.; Jeong, S.Y.; Jeong, Y.H.; Kim, D.S. Experimental study of ground subsidence mechanism caused by sewer pipe cracks. *Appl. Sci.* **2018**, *8*, 679. [CrossRef]
2. Oren, G.; Stroh, N. Antileaks: A device for detection and discontinuation of leakages in domestic water supply systems. *Eur. J. Young Sci. Eng.* **2012**, *1*, 10–13.
3. Kwak, P.J.; Park, S.H.; Choi, C.H.; Lee, H.D.; Kang, J.M.; Lee, I.H. IoT (Internet of Things)-based underground risk assessment system surrounding water pipes in Korea. *Int. J. Control Autom.* **2015**, *8*, 183–190. [CrossRef]
4. Rosdi, M.A.H.M.; Othman, A.N.; Zubir, M.A.M.; Latif, Z.A.; Yusoff, Z.M. Sinkhole susceptibility hazard zones using GIS and Analytical Hierarchical Process (AHP): A case study of Kuala Lumpur and Ampang Jaya. *ISPRS Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2017**, *XLII-4/W5*, 145–151. [CrossRef]
5. Jaya, P. Two Pedestrians Fall Into 3m-Deep Sinkhole in Seoul. *Star Online*. 25 February 2015. Available online: https://www.thestar.com.my/news/world/2015/02/25/sink-hole-seoul/#wGy2vrEth6cJBmhd.99 (accessed on 26 November 2018).
6. De Waele, J.; Gutiérrez, F.; Parise, M.; Plan, L. Geomorphology and natural hazards in karst areas: A review. *Geomprphology* **2011**, *134*, 1–8. [CrossRef]
7. Han, Y.; Hwang, H.W. Discussion on the sinkhole forming mechanism. *Int. J. Adv. Sci. Eng. Technol.* **2017**, *5*, 42–44.
8. Julian, R. Japan Giant Sinkhole in Fukuoka Repaired in a Week Begins to Sink Again. *Daily Mail Online*, 28 November 2016. Available online: https://www.dailymail.co.uk/news/article-3978468/Panic-Japan-giant-sinkhole-repaired-just-week-begins-sink-forcing-road-close-did-carry-repairs-quickly.html (accessed on 26 November 2018).
9. Steve, R.; Haworth, J. Police Officer Killed After Massive Sinkhole Opens Up in Road Swallowing Two Cars. *Mirror*, 6 December 2016. Available online: https://www.mirror.co.uk/news/world-news/man-killed-after-being-swallowed-9397110 (accessed on 26 November 2018).
10. Roger, S. Huge Sinkholes Are Now Appearing in The Wrong Places. *AP News*, 9 May 2017. Available online: https://apnews.com/41a17da407d241769e54085a8118ac7c (accessed on 26 November 2018).
11. Joel, B. Old Pipes, Big Problems: More Than 20 Sinkholes in Asheville. *Citizen Times*, 13 December 2016. Available online: https://www.citizen-times.com/story/news/local/2016/12/13/old-pipes-big-problems-more-than-20-sinkholes-asheville/95152436/ (accessed on 26 November 2018).
12. Hunaidi, O.; Chu, W.; Wang, A.; Guan, W. Detecting leaks in plastic pipes. *J. Am. Water Works Assoc.* **2000**, *92*, 82–94. [CrossRef]
13. Liston, D.A.; Liston, J.D. Leak detection techniques. *J. N. Engl. Water Work. Assoc.* **1992**, *106*, 103–108.
14. Gao, Y.; Brennan, M.J.; Joseph, P.F.; Muggleton, J.M.; Hunaidi, O. A model of the correlation function of leak noise in buried plastic pipes. *J. Sound Vib.* **2004**, *277*, 133–148. [CrossRef]
15. Farley, M.; Liemberger, R. Developing a non-revenue water reduction strategy: Planning and implementing the strategy. *Water Sci. Technol. Water Supply* **2005**, *5*, 41–50. [CrossRef]
16. Lin, M.; Wu, Y.; Wassell, I. Wireless sensor network: Water distribution monitoring system. In Proceedings of the 2008 IEEE Radio and Wireless Symposium, Orlando, FL, USA, 22–24 January 2008; pp. 775–778.
17. Hawari, A.; Alamin, M.; Alkadour, F.; Elmasry, M.; Zayed, T. Automated defect detection tool for closed circuit television (cctv) inspected sewer pipelines. *Autom. Constr.* **2018**, *89*, 99–109. [CrossRef]
18. Hunaidi, O.; Wang, A.; Bracken, M.; Gambino, T.; Fricke, C. Acoustic Methods for Locating Leaks in Municipal Water Pipe Networks. In Proceedings of the International Water Demand Management Conference, Dead Sea, Jordan, 30 May–3 June 2004; pp. 1–14.

19. Craig, F.; Babette, B. *Strategic and Competitive Analysis: Methods and Techniques for Analyzing Business Competition*, 1st ed.; Prentice Hall: Upper Saddle River, NJ, USA, 2002; 457p.
20. Ahn, K.S.; Cho, S.N. System for Detecting Leakage of Water in Conduit Line Installed Underground. WO Patent WO2018105764A1, 14 June 2018.
21. Kim, A. System for Detecting a Pipeline Leaks. K.R. Patent KR 20170075452A, 3 July 2018.
22. Ko, Y.M. Monitoring System for Leak Detection of Waterworks. K.R. Patent KR 101876730B1, 9 August 2018.
23. Merlo, S.A. Remote Pipe Inspection Using a Mounted Camera and Sensor. U.S. Patent US 8087311B2, 4 September 2008.
24. Oh, H.J.; Choi, D.S.; Lee, S.M. Safety and Monitoring Device of Pipeline. K.R. Patent KR 101571366B1, 25 November 2015.
25. Choi, R.G. Sewer Inspection System to Prevent Sinkhole. K.R. Patent KR 101564223B1, 30 October 2015.
26. Ko, Y.M. Monitoring System of Water Leakage and Sinkhole Using Water Leakage Sensor. K.R. Patent KR 101807739B1, 12 December 2017.
27. Yang, B.; Recane, M. Methods and Appratus for Pattern Match Filtering for Real Time Acoustic Pipeline Leak Detection and Location. U.S. Patent US 6389881B1, 21 May 2002.
28. Stephen, M. Remote Pipe Inspection. U.S. Patent US 8087311B2, 4 September 2008.
29. Ggorbel, F.H.; Dabney, J.B. Pipes and Sewer Inspection Means Maintenance Vehicle. U.S. Patent US 7182025B2, 27 Febuary 2018.
30. Kim, K.B.; Shin, S.H.; Kim, S.Y. Mobile Type Monitoring Device for Pipelines. K.R. Patent KR 101753707B1, 5 July 2017.
31. Kim, J.K. System for Detecting Water Leakage of Water Pipe. K.R. Patent KR 101967405B1, 8 March 2017.
32. Rye, D.W.; Yeom, B.W.; Bang, E.S.; Lee, H.J.; Jung, B.J.; Jung, S.W.; Lee, I.W.; Choi, C.H. Method for Evaluating Subsidence Risk in Urban Area. K.R. Patent KR 101808127B1, 12 May 2016.
33. Jung, S.W.; Yeom, B.W.; Ryu, D.W.; Lee, H.J.; Jeong, B.J.; Bang, E.S.; Lee, I.W. Apparatus for Measuring Shear Strength of Soil in Ground Subsidence Envirinment. K.R. Patent KR 101742107B1, 12 May 2015.
34. Gary, P. Sinkhole Detection Systems and Methods. U.S. Patent US 9638593B2, 2 May 2017.
35. Jung, Y.S.; Jung, S.H.; Cho, Y.G.; Park, J.J.; Kim, K.S.; Kang, H.H.; Kim, J.H. Injection Packer Restoration, Reclamation Method and Apparatus for Ground Subsidence. K.R. Patent KR 101849929B1, 18 March 2018.
36. Yang, G.H.; Yu, I.K.; Sim, J.I. Lightweight Soil for Preventing Sinkhole. K.R. Patent KR 101583257B1, 18 December 2014.
37. Kang, T.S.; Park, H.I.; Won, C.H. Paving Structure Capable of Preventing the Falling of the Pedestrian by Small Sinkhole. K.R. Patent KR 101699496B1, 1 April 2015.
38. Hwang, G.; Lee, Q.S.; Woo-Sub, Y. Device for Detecting Change in Underground Medium. U.S. Patent US 20160146760A1, 26 May 2016.
39. Lee, K.M.; Cho, J.H.; Shin, D.H. Sensor for Sensing Sinkhole, Sinkhole Monitoring System, and Method Using Sensor for Sensing Sinkhole. K.R. Patent KR 101680846B1, 13 December 2015.
40. Park, J.K.; Bong, T.G.; Kwon, S.W. System for Monitoring Groundwater with Function of Detecting Sinkhole. K.R. Patent KR 101528831B1, 16 June 2015.
41. Kang, H.J. A Sinkhole Detecting Device. K.R. Patent KR 101704527B1, 8 Febuary 2017.
42. Kang, K.Y.; Kim, C.H. Ground Penetrating Radar Survey Vehicle. K.R. Patent KR 101820805B1, 22 January 2018.
43. Kim, S.S. Switchboard System for Sensing Sinkhole. K.R. Patent KR 101904072B1, 14 November 2017.
44. Kim, Y.J. Sinkhole Exploration Device Using V_{rms}, the Inversion Process and Signal-to-Noise Ratio Upgrade of Permeable Underground Radar Exploration Using Common Reflection Surface Method. K.R. Patenet KR 101799813B1, 21 November 2017.
45. Jerry, S. Sinkhole Detector. U.S. Patent US 9552716B1, 24 January 2017.
46. Ko, B.C.; Jang, J.H.; Shin, S.Y.; Lee, E.J.; Lee, D.J. Sinkhole Detection System and Method Using a Drone-Based Thermal Camera and Image Processing. K.R. Patent KR 101857961B1, 4 October 2016.
47. Lee, H.J. Sinkholes Prevention Methods by Closing Settlement. K.R. Patent KR 101553599B1, 17 September 2015.
48. Ryu, D.W.; Kim, E.; Lee, K.; Yum, B.W.; Lee, I.; Lee, J.; Jeong, W.S.; Lee, H.; Jung, B.; Bnag, S.E.; et al. Method for Detecting Change in Underground Environment by Using Magnetic Induction, Detection Sensor and Detection System. U.S. Patent US 20180209787A1, 14 July 2015.
49. Ko, B.C.; Jang, J.H.; Shin, S.Y.; Joo, L.E. A Method for Construction of Simulation Mock Sinkhole. K.R. Patent KR 20180050045A, 14 May 2018.

50. Jung, S.W.; Yeom, B.W.; Ryu, D.W.; Lee, H.J.; Jung, B.J.; Bang, E.S.; Lee, I.H. Monitoring System and Method for Predicting Urban Sinkhole Measured by Suction Stress and Pore Water Pressure. K.R. Patent KR 101779017B1, 19 September 2017.
51. Jung, S.W.; Yeom, B.W.; Rye, D.W.; Lee, H.J.; Jung, B.J.; Bang, E.S.; Lee, I.H. System and Method for Predicting Urban Sinkhole Based on Shear Strength Measured by Vane Tester. K.R. Patent KR 101781409B1, 26 September 2017.
52. Wy, Y.H. Sinkhole Experimental Apparatus and Its Manufacturing Method. K.R. Patent KR 101890268B1, 29 September 2018.
53. McVay, M.; Tran, K.T. Detection of Sinkholes or Anomalies. U.S. Patent US 10088586B2, 2 October 2018.
54. Ali, S.; Ashraf, A.; Qaisar, S.B.; Afridi, M.K.; Saeed, H.; Rashid, S.; Felemban, E.A.; Sheikh, A.A. SimpliMote: A Wireless Sensor Network Monitoring Platform for Oil and Gas Pipelines. *IEEE Syst. J.* **2018**, *12*, 778–789. [CrossRef]
55. El-Darymli, K.; Khan, F.; Ahmed, M.H. Reliability Modeling of Wireless Sensor Network for Oil and Gas Pipelines Monitoring. *Sens. Transducers J.* **2009**, *106*, 6–26.
56. Abdelhafidh, M.; Fourati, M.; Fourati, L.C.; Laabidi, A. An investigation on wireless sensor networks pipeline monitoring system. *Int. J. Wirel. Mob. Comput.* **2018**, *14*, 25. [CrossRef]
57. Sheltami, T.R.; Bala, A.; Shakshuki, E.M. Wireless sensor networks for leak detection in pipelines: A survey. *J. Ambient Intell. Humaniz. Comput.* **2016**, *7*, 347–356. [CrossRef]
58. Bensaleh, M.S.; Qasim, S.M. Optimal Solutions for Water Pipeline Monitoring using Wireless Sensor Network [Extended Abstract]. In Proceedings of the SemiCon China-CSTIC Conference, Shanghai, China, 16–17 March 2014; pp. 1–4.
59. AL-Kadi, T.; AL-Tuwaijri, Z.; AL-Omran, A. Wireless sensor networks for leakage detection in underground pipelines: A Survey Paper. *Procedia Comput. Sci.* **2013**, *21*, 491–498. [CrossRef]
60. Adedeji, K.B.; Hamam, Y.; Abe, B.T.; Abu-Mahfouz, A.M. Towards achieving a reliable leakage detection and localization algorithm for application in water piping networks: An Overview. *IEEE Access* **2017**, *5*, 20272–20285. [CrossRef]
61. Datta, S.; Sarkar, S. A review on different pipeline fault detection methods. *J. Loss Prev. Process Ind.* **2016**, *41*, 97–106. [CrossRef]
62. BenSaleh, M.S.; Qasim, S.M.; Abid, M.; Jmal, M.W.; Karray, F.; Obeid, A.M. Towards realisation of wireless sensor network-based water pipeline monitoring systems: A comprehensive review of techniques and platforms. *IET Sci. Meas. Technol.* **2016**, *10*, 420–426.
63. BenSaleh, M.S.; Qasim, S.M.; Obeid, A.M.; Garcia-Ortiz, A. A review on wireless sensor network for water pipeline monitoring applications. In Proceedings of the 2013 IEEE International Conference on Collaboration Technologies and Systems (CTS), San Diego, CA, USA, 20–24 May 2013; pp. 128–131.
64. Sohraby, K.; Minoli, D.; Znati, T.F. *Wireless Sensor Networks: Technology, Protocols, and Applications*, 1st ed.; Wiley Publication: Hoboken, NJ, USA, 2007; 328p.
65. Yick, J.; Mukherjee, B.; Ghosal, D. Wireless sensor network survey. *Comput. Netw.* **2008**, *52*, 2292–2330. [CrossRef]
66. Vuran, M.C.; Akyildiz, I.F. Channel model and analysis for wireless underground sensor networks in soil medium. *Phys. Commun.* **2010**, *3*, 245–254. [CrossRef]
67. Ilyas, M. *The Handbook of Ad Hoc Wireless Networks*, 1st ed.; CRC Press: Boca Raton, FL, USA, 2003; 624p.
68. Labiod, H.; Afifi, H.; DeSantis, C. *Wi-Fi, Bluetooth, Zigbee and WiMAX, 1st ed*; Springer: Berlin, Germany, 2007; ISBN 1402053975.
69. Lee, J.S.; Su, Y.W.; Shen, C.C. A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi. In Proceedings of the 33rd Annual Conference of the IEEE Industrial Electronics Society (IECON), Taipei, Taiwan, 5–8 November 2007; pp. 46–51.
70. Pothuganti, K.; Chitneni, A. A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi. *Adv. Electron. Electr. Eng.* **2014**, *4*, 655–662.
71. Almazyad, A.; Seddiq, Y.; Alotaibi, A.; Al-Nasheri, A.; BenSaleh, M.; Obeid, A.; Qasim, S.; Almazyad, A.S.; Seddiq, Y.M.; Alotaibi, A.M.; et al. A Proposed Scalable Design and Simulation of Wireless Sensor Network-Based Long-Distance Water Pipeline Leakage Monitoring System. *Sensors* **2014**, *14*, 3557–3577. [CrossRef] [PubMed]

72. Ng, K.S.; Chen, P.Y.; Tseng, Y.C. A design of automatic water leak detection device. In Proceedings of the 2017 IEEE 2nd International Conference on Opto-Electronic Information Processing (ICOIP), Singapore, 7–9 July 2017; pp. 70–73.
73. Cattani, M.; Boano, C.A.; Steffelbauer, D.; Kaltenbacher, S.; Günther, M.; Römer, K.; Fuchs-Hanusch, D.; Horn, M. Adige: An efficient smart water network based on long-range wireless technology. In Proceedings of the 3rd International Workshop on Cyber-Physical Systems for Smart Water Networks—CySWATER '17, Pittsburgh, PA, USA, 21 April 2017; pp. 3–6.
74. Karray, F.; Garcia-Ortiz, A.; Jmal, M.W.; Obeid, A.M.; Abid, M. EARNPIPE: A Testbed for Smart Water Pipeline Monitoring Using Wireless Sensor Network. *Procedia Comput. Sci.* **2016**, *96*, 285–294. [CrossRef]
75. Sun, Z.; Wang, P.; Vuran, M.C.; Al-Rodhaan, M.A.; Al-Dhelaan, A.M.; Akyildiz, I.F. MISE-PIPE: Magnetic induction-based wireless sensor networks for underground pipeline monitoring. *Ad Hoc Netw.* **2011**, *9*, 218–227. [CrossRef]
76. Kuwano, R.; Horii, T.; Kohashi, H.; Yamauchi, K. Defects of sewer pipes causing cave-in's in the road. In Proceedings of the 5th International Symposium on New Technologies for Urban Safety of Mega Cities in Asia, Phuket, Thailand, 16–17 November 2006; pp. 347–353.
77. Kim, J.H.; Sharma, G.; Boudriga, N.; Iyengar, S.S.; Prabakar, N. Autonomous pipeline monitoring and maintenance system: A RFID-based approach. *EURASIP J. Wirel. Commun. Netw.* **2015**, *2015*, 262. [CrossRef]
78. Stoianov, I.; Nachman, L.; Madden, S.; Tokmouline, T. PIPENETa wireless sensor network for pipeline monitoring. In Proceedings of the 6th International Conference on Information Processing in Sensor Networks—IPSN '07, Cambridge, MA, USA, 25–27 April 2007; ACM Press: New York, NY, USA, 2007; pp. 264–273.
79. Stoianov, I.; Nachman, L.; Whittle, A.; Madden, S.; Kling, R. Sensor Networks for Monitoring Water Supply and Sewer Systems: Lessons from Boston. In Proceedings of the 8th Annual Water Distribution Systems Analysis Symposium (WDSA), Cincinnati, OH, USA, 27–30 August 2006; pp. 1–17.
80. Nassiraei, A.A.F.; Kawamura, Y.; Ahrary, A.; Mikuriya, Y.; Ishii, K. A New Approach to the Sewer Pipe Inspection: Fully Autonomous Mobile Robot "KANTARO". In Proceedings of the IECON 2006—32nd Annual Conference on IEEE Industrial Electronics, Paris, France, 6–10 November 2006; pp. 4088–4093.
81. Cheng, J.C.P.; Wang, M. Automated detection of sewer pipe defects in closed-circuit television images using deep learning techniques. *Autom. Constr.* **2018**, *95*, 155–171. [CrossRef]
82. Lai, T.T.T.; Chen, W.J.; Li, K.H.; Huang, P.; Chu, H.H. TriopusNet: Automating wireless sensor network deployment and replacement in pipeline monitoring. In Proceedings of the 2012 ACM/IEEE 11th International Conference on Information Processing in Sensor Networks (IPSN), Beijing, China, 16–20 April 2012; pp. 61–71.
83. Daadoo, M.; Daraghmi, Y. Smart Water Leakage Detection Using Wireless Sensor Networks (SWLD). *Int. J. Netw. Commun.* **2017**, *7*, 1–16.
84. Shinozuka, M.; Chou, P.H.; Kim, S.; Kim, H.R.; Yoon, E.; Mustafa, H.; Karmakar, D.; Pul, S. Nondestructive monitoring of a pipe network using a MEMS-based wireless network. In Proceedings of the SPIE Smart Structures and Matrials and Non Distructive Evaluation and Health Monitoring, San Diego, CA, USA, 12 April 2010; p. 76490P.
85. Kadri, A.; Abu-Dayya, A.; Trinchero, D.; Stefanelli, R. Autonomous sensing for leakage detection in underground water pipelines. In Proceedings of the 2011 Fifth IEEE International Conference on Sensing Technology, Palmerston North, New Zealand, 28 November–1 December 2011; pp. 639–643.
86. Mustafa, H.; Chou, P.H. Embedded Damage Detection in Water Pipelines Using Wireless Sensor Networks. In Proceedings of the 2012 IEEE 14th International Conference on High Performance Computing and Communication & 2012 IEEE 9th International Conference on Embedded Software and Systems, Liverpool, UK, 25–27 June 2012; pp. 1578–1586.
87. Sadeghioon, A.; Metje, N.; Chapman, D.; Anthony, C.; Sadeghioon, A.M.; Metje, N.; Chapman, D.N.; Anthony, C.J. SmartPipes: Smart Wireless Sensor Networks for Leak Detection in Water Pipelines. *J. Sens. Actuator Netw.* **2014**, *3*, 64–78. [CrossRef]
88. Ismail, M.I.M.; Dziyauddin, R.A.; Samad, N.A.A. Water pipeline monitoring system using vibration sensor. In Proceedings of the 2014 IEEE Conference on Wireless Sensors (ICWiSE), Subang, Malaysia, 26–28 October 2014; pp. 79–84.

89. Kim, J.H.; Sharma, G.; Boudriga, N.; Iyengar, S.S. SPAMMS: A sensor-based pipeline autonomous monitoring and maintenance system. In Proceedings of the 2010 Second International Conference on Communication Systems and NETworks (COMSNETS 2010), Bangalore, India, 5–9 January 2010; pp. 1–10.
90. Yoon, S.H.; Ye, W.; John, H.; Littlefield, B.; Hahabi, S.C. SWATS: Wireless Sensor Networks for Steamflood and Waterflood Pipeline Monitoring. *IEEE Netw.* **2011**, *25*, 50–56. [CrossRef]
91. Lim, J.S.; Kim, J.; Friedman, J.; Lee, U.; Vieira, L.; Rosso, D.; Gerla, M.; Srivastava, M.B. SewerSnort: A drifting sensor for in situ Wastewater Collection System gas monitoring. *Ad Hoc Netw.* **2013**, *11*, 1456–1471. [CrossRef]
92. Metje, N.; Chapman, D.N.; Cheneler, D.; Ward, M.; Thomas, A.M.; Metje, N.; Chapman, D.N.; Cheneler, D.; Ward, M.; Thomas, A.M. Smart Pipes—Instrumented Water Pipes, Can This Be Made a Reality? *Sensors* **2011**, *11*, 7455–7475. [CrossRef] [PubMed]
93. Constantinou, S.; Van Rooy, J.L. Sinkhole and subsidence size distribution across dolomitic land in Gauteng. *J. S. Afr. Inst. Civ. Eng.* **2018**, *60*, 2–8. [CrossRef]
94. James, R. Foundation Engineering Problems and Hazards in Karst Terranes. Maryland Department of Natural Resources, 2015. Available online: http://www.mgs.md.gov/geology/geohazards/engineering_problems_in_karst.html (accessed on 26 November 2018).
95. Stop Sinkholes Before They Start. Municipal Sewer and Water. 2017. Available online: https://www.mswmag.com/online_exclusives/2017/10/stop_sinkholes_before_they_start_sc_00125 (accessed on 26 November 2018).
96. Road Cave-in and Special Countermeasure. Seoul Metropolitan Government, 2015. Available online: http://english.seoul.go.kr/#none (accessed on 3 May 2019).
97. Sevil, J.; Gutiérrez, F.; Zarroca, M.; Desir, G.; Carbonel, D.; Guerrero, J.; Linares, R.; Roqué, C.; Fabregat, I. Sinkhole investigation in an urban area by trenching in combination with GPR, ERT and high-precision leveling. Mantled evaporite karst of Zaragoza city, NE Spain. *Eng. Geol.* **2017**, *231*, 9–20. [CrossRef]
98. Xu, J.; He, J.; Zhang, L. Collapse prediction of karst sinkhole via distributed Brillouin optical fiber sensor. *Measurement* **2017**, *100*, 68–71. [CrossRef]
99. Desir, G.; Gutiérrez, F.; Merino, J.; Carbonel, D.; Benito-Calvo, A.; Guerrero, J.; Fabregat, I. Rapid subsidence in damaging sinkholes: Measurement by high-precision leveling and the role of salt dissolution. *Geomorphology* **2018**, *303*, 393–409. [CrossRef]
100. Intrieri, E.; Gigli, G.; Nocentini, M.; Lombardi, L.; Mugnai, F.; Fidolini, F.; Casagli, N. Sinkhole monitoring and early warning: An experimental and successful GB-InSAR application. *Geomorphology* **2015**, *241*, 304–314. [CrossRef]
101. Cooper, A.H.; Farrant, A.R.; Price, S.J. The use of karst geomorphology for planning, hazard avoidance and development in Great Britain. *Geomorphology* **2011**, *134*, 118–131. [CrossRef]
102. Comerci, V.; Vittori, E.; Cipolloni, C.; Di Manna, P.; Guerrieri, L.; Nisio, S.; Succhiarelli, C.; Ciuffreda, M.; Bertoletti, E. Geohazards Monitoring in Roma from InSAR and In Situ Data: Outcomes of the PanGeo Project. *Pure Appl. Geophys.* **2015**, *172*, 2997–3028. [CrossRef]
103. Nouioua, I.; Laid Boukelloul, M.; Fehdi, C.; Baali, F. Detecting Sinkholes Using Ground Penetrating Radar in Drâa Douamis, Cherea Algeria: A Case Study. *Electron. J. Geotech. Eng.* **2013**, *18*, 1337–1349.
104. Al-fares, W.; Bakalowicz, M.; Guérin, R.; Dukhan, M. Analysis of the karst aquifer structure of the Lamalou area (Hérault, France) with ground penetrating radar. *J. Appl. Geophys.* **2002**, *51*, 97–106. [CrossRef]
105. Pueyo Anchuela, Ó.; Casas Sainz, A.M.; Pocoví Juan, A.; Gil Garbí, H. Assessing karst hazards in urbanized areas. Case study and methodological considerations in the mantle karst from Zaragoza city (NE Spain). *Eng. Geol.* **2015**, *184*, 29–42. [CrossRef]
106. Yacine, A.; Ridha, M.M.; Laid, H.M.; Abderahmane, B. Karst Sinkholes Stability Assessment in Cheria Area, NE Algeria. *Geotech. Geol. Eng.* **2014**, *32*, 363–374. [CrossRef]
107. Al-kouri, O.; Al Fugara, A.; Al-Rawashdeh, S.; Sadoun, B.; Pradhan, B. Geospatial modeling for sinkholes hazard map based on GIS & RS data. *J. Geogr. Inf. Syst.* **2013**, *5*, 584–592.
108. Galve, J.P.; Lucha, P.; Castañeda, C.; Bonachea, J.; Guerrero, J. Integrating geomorphological mapping, trenching, InSAR and GPR for the identification and characterization of sinkholes: A review and application in the mantled evaporite karst of the Ebro Valley (NE Spain). *Geomorphology* **2011**, *134*, 144–156.
109. Carbonel, D.; Rodríguez, V.; Gutiérrez, F.; McCalpin, J.P.; Linares, R.; Roqué, C.; Zarroca, M.; Guerrero, J.; Sasowsky, I. Evaluation of trenching, ground penetrating radar (GPR) and electrical resistivity tomography (ERT) for sinkhole characterization. *Earth Surf. Process. Landf.* **2014**, *39*, 214–227. [CrossRef]

110. Nouioua, I.; Rouabhia, A.; Fehdi, C.; Boukelloul, M.L.; Gadri, L.; Chabou, D.; Mouici, R. The application of GPR and electrical resistivity tomography as useful tools in detection of sinkholes in the Cheria Basin (northeast of Algeria). *Environ. Earth Sci.* **2013**, *68*, 1661–1672. [CrossRef]
111. Joyce, K.E.; Samsonov, S.V.; Levick, S.R.; Engelbrecht, J.; Belliss, S. Mapping and monitoring geological hazards using optical, LiDAR, and synthetic aperture RADAR image data. *Nat. Hazards* **2014**, *73*, 137–163. [CrossRef]
112. Kobal, M.; Bertoncelj, I.; Pirotti, F.; Dakskobler, I.; Kutnar, L. Using Lidar Data to Analyse Sinkhole Characteristics Relevant for Understory Vegetation under Forest Cover—Case Study of a High Karst Area in the Dinaric Mountains. *PLoS ONE* **2015**, *10*, e0122070. [CrossRef]
113. VanSchoor, M. Detection of sinkholes using 2D electrical resistivity imaging. *J. Appl. Geophys.* **2002**, *50*, 393–399. [CrossRef]
114. Ge, L.; Chang, H.-C.; Rizos, C. Mine Subsidence Monitoring Using Multi-source Satellite SAR Images. *Photogramm. Eng. Remote Sens.* **2007**, *73*, 259–266. [CrossRef]
115. Filin, S.; Baruch, A. Detection of Sinkhole Hazards using Airborne Laser Scanning Data. *Photogramm. Eng. Remote Sens.* **2010**, *76*, 577–587. [CrossRef]
116. Suh, J.; Choi, Y. Mapping hazardous mining-induced sinkhole subsidence using unmanned aerial vehicle (drone) photogrammetry. *Environ. Earth Sci.* **2017**, *76*, 144. [CrossRef]
117. Kim, K.; Park, D.-H.; Lee, J.; Jin, S. UGS middleware for monitoring state of underground utilities. In Proceedings of the 2015 IEEE International Conference on Information and Communication Technology Convergence (ICTC), Jeju, Korea, 28–30 October 2015; pp. 1183–1185.
118. Kwak, P.J.; Park, S.H.; Choi, C.H.; Lee, H.D. Safety Monitoring Sensor for Underground Subsidence Risk Assessment Surrounding Water Pipeline. *J. Sens. Sci. Technol.* **2015**, *24*, 306–310. [CrossRef]
119. Al-Halbouni, D.; Holohan, E.P.; Taheri, A.; Schöpfer, M.P.J.; Emam, S.; Dahm, T. Geomechanical modelling of sinkhole development using distinct elements: Model verification for a single void space and application to the Dead Sea area. *Solid Earth* **2018**, *9*, 1341–1373. [CrossRef]
120. Oz, I.; Eyal, S.; Yoseph, Y.; Ittai, G.; Elad, L.; Haim, G. Salt dissolution and sinkhole formation: Results of laboratory experiments. *JGR Earth Surf.* **2016**, *121*, 1746–1762. [CrossRef]
121. Tao, X.; Ye, M.; Wang, X.; Wang, D.; Castro, R.; Zhao, J. Experimental and Numerical Investigation of Sinkhole Development and Collapse in Central Florida. In Proceedings of the Fourteenth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst; University of South Florida Tampa Library: Tampa, FL, USA, 2015; pp. 501–506.
122. Dimitrakopoulos, G. Sustainable mobility leveraging on 5G mobile communication infrastructures in the context of smart city operations. *Evol. Syst.* **2017**, *8*, 157–166. [CrossRef]
123. Kang, J.; Choi, C.; Kwak, P.J.; Kim, J.; Park, S.H.; Park, Y. Ground subsidence monitoring and risk assessment around water supply and sewerage. *J. Korean Soc. Civ. Eng.* **2017**, *65*, 22–27.
124. Gray, K.M. Central Florida Sinkhole Evaluation. In *District Geotechnical Engineer*; Florida Department of Transportation: Tallahassee, FL, USA, 2014.