International Journal of Electrical and Computer Engineering (IJECE)
Vol. 13, No. 2, April 2023, pp. 2214~2222
ISSN: 2088-8708, DOI: 10.11591/ijece.v13i2.pp2214-2222

Landslide early warning systems: a perspective from the internet of things

Vladimir Henao-Céspedes[1], Yeison Alberto Garcés-Gómez[1], María Nancy Marín Olaya[2]
[1]Unidad Académica de Formación en Ciencias Naturales y Matemáticas, Universidad Católica de Manizales, Manizales, Colombia
[2]Facultad de Ingeniería y Arquitectura, Universidad Católica de Manizales, Manizales, Colombia

Article Info

Article history:

Received Mei 16, 2022
Revised Sep 15, 2022
Accepted Nov 2, 2022

Keywords:

Early warning system
Internet of things
Landslide
Risk
Scientific production

ABSTRACT

Populations located in the vicinity of slopes and soils derived from volcanic ash are constantly at risk due to the possibility of landslides. Such is the case of the city of Manizales, Colombia, which, due to its geomorphological characteristics, has experienced a significant number of landslides that have caused human and economic losses. The Internet of things (IoT) has allowed important technological advances for monitoring, thanks to the low cost and wide coverage of IoT-based systems. Slope monitoring and the development of landslide early warning systems (EWS) have been positively impacted by IoT developments, which shows a relationship. The objective of this article is to review, from the scientific production, the relationship between IoT and EWS. For this purpose, a fragmenting-deriving-combining methodology is applied to focus on a research trends analysis of the subject, from macro-areas such as IoT and EWS to micro areas such as EWS by IoT-based landslides. Finally, the analysis concluded that the conceptual models of IoT and EWS for landslides have some correspondence in some of their layers.

Corresponding Author:

Vladimir Henao Céspedes
Unidad Académica de Formación en Ciencias Naturales y Matemáticas, Universidad Católica de Manizales
Cra 23 No 60-63, Manizales, Caldas, Colombia
Email: vhenao@ucm.edu.co

1. INTRODUCTION

A mountainous area, with steep slopes, hillsides, in combination with highly permeable soils derived from volcanic ash, which allow infiltration and accumulation of rainwater [1], are potential landslide-causing factors [2]. Such is the case of the city of Manizales, in Colombia, located on the Andes Mountain range. In this city, due to the aforementioned characteristics, 1,141 disastrous events have occurred in the period 1917 to 2007, of which 85% have been landslides, generating 530 deaths, 4,000 victims, 110,000 people affected, 1,500 houses destroyed and 5,000 affected, and economic losses of US$ 5 million [3], and it is as a result of these events that, since the 1970s, research has been carried out to generate risk management strategies.

The most recent case of large landslides in Manizales was on April 19, 2017, caused by heavy rains, with rainfall levels exceeding 150 mm in certain areas of the city, specifically in the urban settlement called Aranjuez, located in the area of one of the large landslides that occurred that day as shown in Figure 1 [4], rainfall levels were 104 mm [5], [6]. These landslides caused 17 loss of life, 730 homes evacuated, and 259 families left homeless as shown in Figure 2 [7], and a total of 3,126 people were affected [8].

To contribute to the risk management strategies implemented in the city, it is necessary to develop and implement monitoring technologies based on the internet of things (IoT), which allow the collection of information in a wide spatial and temporal window, to better understand the dynamics of the slopes that represent a risk in the city, and to issue early warnings thus forming an early warning system (EWS), which allows generating warnings or levels of warning of any adverse effects on the safety of the population [9].

Figure 1. Panoramic view of landslides on Sancancio hill, on April 19, 2017 [4]

Figure 2. Destruction in the Aranjuez neighborhood, near Sancancio hill [7]

In order for an EWS to operate correctly, it must have a significant amount of accurate information about the area being monitored. For this, it is necessary to define variables of interest, in the case of the EWS for landslides these are variables associated with the slope. This allows for defining the type of sensors that are necessary to perform the monitoring, these sensors must cover the largest possible area, for which IoT technology is used. The area requirement is possible with IoT thanks mainly to the ease that these systems offer to be able to take them to areas of difficult access, the low cost of implementation, low power consumption, and the fact that they are easy to install [10] and the types of network infrastructure used called low power wide area network (LPWAN). LPWAN technologies are designed for long-range communications, low power consumption, low cost, and scalability, and allow multiple nodes (measurement stations with their respective sensors) to communicate the data obtained to a gateway that subsequently forwards them to cloud storage where they can be managed for further analysis. Regarding the use of IoT in early warning systems there are authors who have presented reviews on this topic. Pecoraro *et al.* [11] made a very complete study on different landslide early warning systems, including some that do not make use of IoT, in which he presents important data such as inventories on the parameters monitored and instruments used. On the other hand, Esposito *et al.* [12] presented a review on the use of IoT in early warning systems for floods, earthquakes, tsunamis, and landslides. In relation to landslides, the authors present the sensors, protocols, and techniques used by some early warning systems developed.

This paper aims to present in detail the relationship between the IoT layer model and the EWS layer model, based on research trends analysis on landslide EWS implemented exclusively with IoT. For the above, the authors perform an analysis of the research trends on EWS of landslides implemented exclusively with IoT. Starting from the definition of an object of study and a theoretical framework, related, that allows defining the information search strategy.

2. METHOD

To analyze the relationship between IoT and EWS, it is necessary to establish a bibliometric approach to the subject. Bibliometrics allows the application of statistical methods and models to the study of bibliographic data. It allows, using quantitative methods, to determine the intellectual structure of any scientific field [13]. In the present study, bibliometric indicators are used to represent bibliographic data such as a total number of articles, the total number of articles, and a total number of articles [14], this can be used to measure productivity in the topic of interest and to define the authors who have contributed the most.

For data collection, a fragmenting-deriving-combining (FDC) framework was generated. First, the facets of the background review were defined, such as the object of study and theoretical framework Table 1. Subsequently, keywords associated with the established facets are “derived”. Finally, the derived keywords are “combined”, and the search equations are generated, which can be seen in Table 2. In this review, the bibliographic data used were obtained from the main collection of Scopus, using the search equations, shown in Table 2 [15]. Table 2 allows us to visualize the hierarchical levels of the search. First, a macro search is performed on the topic of the IoT to visualize the dynamics of scientific production and thematic areas. Then a more particularized search is performed, where the relationship between IoT and mass movements can be evidenced. Finally, a micro-level search is performed, where only results showing a relationship between IoT, mass movements, and early warning systems are filtered.

Table 1. Faces of background screening

Faces	Derived keywords
Object of study	"Early warning systems"
Theoretical framework	"Disaster risk management", "mass movement" "landslides"
Technology	"Internet of things", "Web of things", "WSN"

Table 2. Search equations

("Internet of things" OR "Web of things" OR "WSN")
(("early warning system" OR "EWS" OR "early warning monitoring system "OR "EWMS") AND ("Internet of things" OR "Web of things" OR "WSN"))
(("early warning system" OR "EWS" OR "early warning monitoring system "OR "EWMS") AND ("Internet of things" OR "Web of things" OR "WSN") AND ("mass movement" OR "landslide"))

3. RESULTS AND DISCUSSION

The IoT concept was introduced between 2008 and 2009 [16], but the related scientific production, as can be observed in Figure 3, has been around for years, exactly since 2002, and since 2012 it has presented an important increase. The scientific production begins in 2002, with the publication: "The internet of things" by Lee [17] related to radio-frequency identification (RFID)-based techniques for supply chain optimization. In 2004, Gershenfeld *et al.* [18] told how the origin of the Internet would lead to things being able to exchange information with computers, the beginnings of the IoT. That is what is described, today, as having devices "things" that are connected, sharing, and obtaining information, which is used in research in different thematic areas.

Concerning the scientific production that relates IoT and EWS, this has emerged since 2006 with a single article, and again became active in 2011, and has presented a significant increase from 2016 to the present as shown in Figure 4, presenting 670 articles in that time window (2011 to 2020). The above result presents a coincidence with the increase in scientific production exclusive to IoT, seen in Figure 3. When the search includes the topic of mass movements, the scientific production shows a significant reduction, generating a result of 103 articles in a time window from 2011 to 2020 as shown in Figure 5 with an annual growth rate of 50.34%. Figure 6 shows the 20 most cited authors, and Table 3 shows the technologies and contributions made by authors presenting EWS developments.

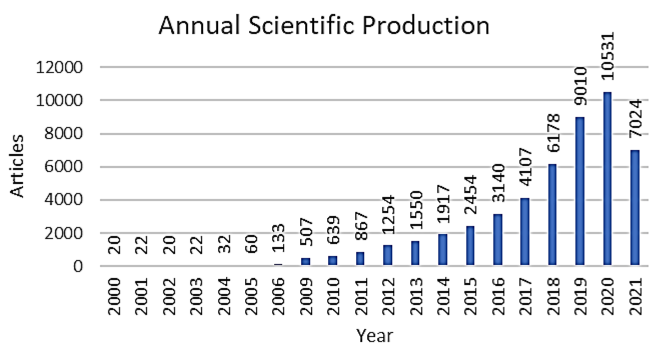

Figure 3. Annual scientific production in the area of the IoT, period 2002-2020

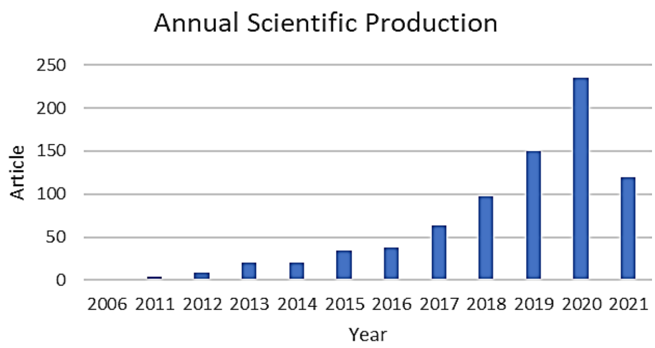

Figure 4. Annual scientific production in the area of IoT and EWS, period 2011 to 2020

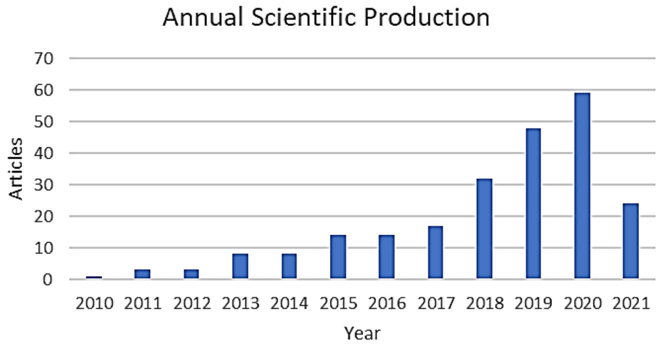

Figure 5. Annual scientific production IoT, EWS, and mass movements

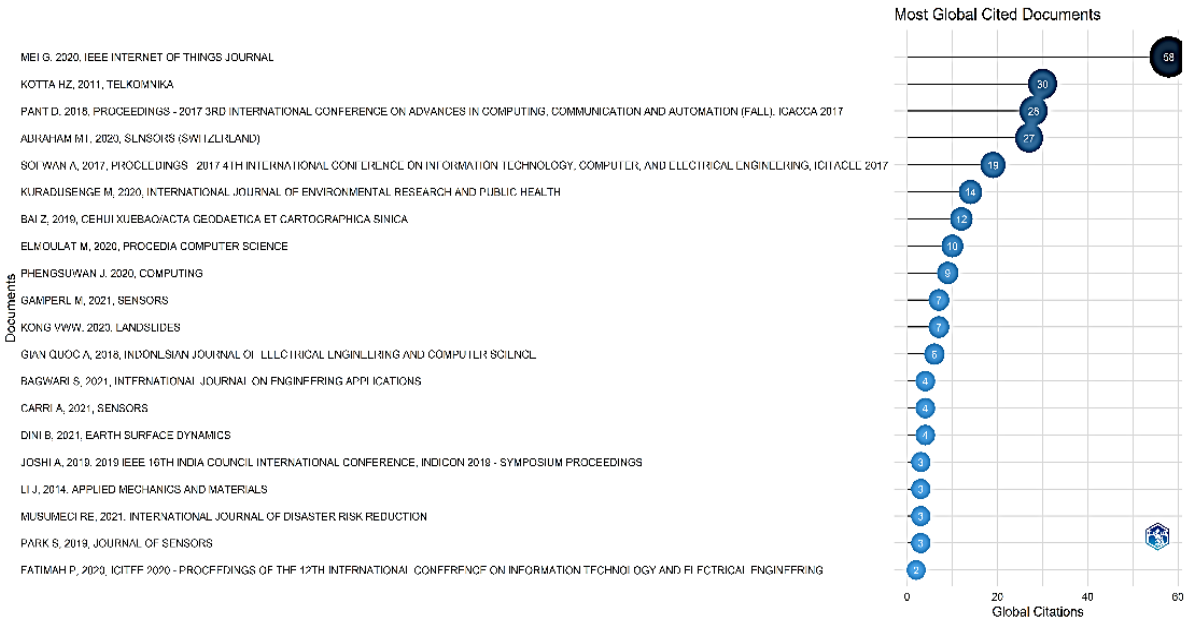

Figure 6. Most global cited documents

In Table 3, it is possible to observe that the most cited authors in the consulted field, propose the development of EWS systems mostly using long range (LoRa) networks and their respective protocols to communicate the sensors, which are also mostly a combination of weather sensors and soil sensors. On the other hand, the emerging use of artificial intelligence (AI) techniques and predictive data analysis models applied to the data collected by the monitoring systems can be appreciated. The above described leads to understand that EWS systems involve all the layers of the IoT model proposed by Cisco [19], showing the relationship between EWS and IoT.

To understand the relationship between an EWS and IoT, it is necessary to understand the functions that an EWS focused on mass movements (landslides) must fulfill. An EWS must guarantee a timely flow of information between governmental institutions and the community exposed to risk, to make decisions focused on risk reduction and provide an effective response. To guarantee the above, an EWS should consider the following elements: i) risk awareness, ii) close follow-up or monitoring, iii) hazard analysis and forecasting, iv) communication or broadcasting of alerts and warnings, and v) local capabilities to respond to the warning received [20].

In addition to the above elements, for the EWS to be reliable, it is necessary, to have i) an understanding of the sliding process, ii) historical knowledge of triggering factors (e.g., precipitation), iii) an effective monitoring program, iv) data interpretation, v) decision making, including the possibility of human intervention, vi) public tolerance to false alarms or fake news, vii) communication system, viii) pre-established action plans for implementation, and ix) feedback loop and adaptability of the system and to the "new" knowledge [21].

Table 3. Top-cited articles presenting EWS developments

Article	Technology	Results-contributions
Wireless sensor network for landslide monitoring in Nusa Tenggara Timur [22].	Perform Y- and X-axis tilt measurements with an accelerometer. Implement an ad-hoc network, connecting several nodes to a gateway and sending the information to a data center.	With the obtained data they define thresholds of accelerometer measurements for the X and Y axes. A threshold from a position of 0.2 g to 0.49 g shows the occurrence of slow ground motion. A value of 0.5 g shows significant changes in ground motion and a value of 1 g or more could cause a disaster. The system is not yet incorporated to generate early warnings.
A study on the slope failure monitoring of a model slope by the application of a displacement sensor [23].	They use several motion sensors deployed in two test slopes and these are connected as an IoT end device in a LoRa network to a gateway that subsequently sends the data to an IoT server.	They develop a slope movement sensor, this sensor is tested on two slopes of different heights, and at different heights they generate cut sections to observe the displacement signals obtained by the sensors and define the time and the precursors of slope failure. The system is not incorporated into an EWS.
IoT-based geotechnical monitoring of unstable slopes for landslide early warning in the Darjeeling Himalayas [24].	They make use of a micro-electro-mechanical system (MEMS) to measure the slope angle, a volumetric water content sensor embedded 30 cm in the slope to measure the water content in the slope. The slope sensor is located inside a box in the ground, attached to a steel rod from which a wireless transmission kit is located at the top outside the slope.	It performs measurements of tilt and water variations in the slope, during a few rainy seasons. According to the authors, the slope data are effective for monitoring slow movements and predicting failure in advance.
Wireless sensor network design for landslide warning system in IoT architecture [25]	They realize a network of nodes, each node is composed of 4 sensors of temperature, humidity, land movement, and soil moisture, and an ATmega 2560 microcontroller. Data communication is done over a GSM network. The data is received in a server and a My SQL database.	Analyze graphically the differences in the measurements obtained over a period of time and calculate for each parameter the average difference.
Rainfall-induced landslide prediction using machine learning models: the case of Ngororero District, Rwanda [26]	It makes use of predictive models: random forest and logistic regression. The data used for the models are rainfall, land cover, soil depth, soil types, and soil type.	The results provided by the models indicate a good correlation between 5 days antecedent precipitation and the occurrence of landslides.
Edge computing and artificial intelligence for landslide monitoring [27]	A network of sensors and multi agent system (MAS). They measured states of ground temperature, vibration, rainfall. They implemented a LoRa network with a weather node and several ground nodes. The data was sent to Edge AI-IoT architecture uses Kubernetes and Docker.	They succeed in moving data processing from the cloud to the edge to optimize bandwidth, improving latency and obtaining a shorter reaction time.
Internet of things geosensor network for cost-effective landslide early warning systems [28]	They designed a system consisting of the following sensors: horizontal continuous shear monitor, extensometer, piezometers. The system was deployed using a LoRa network.	The location of the sensors should be made according to the expected slip processes. These low-cost systems work well for large landslides except for slow processes.
Flexible configuration of wireless sensor network for monitoring of rainfall-induced landslide [29]	Design a sensor network using ZigBee as communication protocol. They used temperature and moisture sensors, and an accelerometer. Performed an integration of star and tree topology.	The results obtained by the authors show a better performance of the proposed system as opposed to the systems that only use star topology or the star topology.
Design of landslide monitoring and early warning system based on internet of things [30]	They deploy a network of stations with accelerometers, humidity, and temperature sensors, which communicate this information through a General packet radio service (GPRS) network.	According to the authors this design greatly improves the efficiency of geological disaster monitoring management and the ability to prevent and manage.

On the other hand, the EWS must consider the unpredictability of landslides and the rapid change of the parameters that cause them [31], i.e., must have the capacity to measure and analyze triggering indicators, to have continuous information on landslide activity and/or the causes that could favor them [32]. A case of triggering indicators is rainfall data [33], [34]. These data are important to generate precipitation thresholds that can be associated with slope stability and instability, thus identifying landslide precursor events. The transition between stability and instability is not easily conceivable, therefore, in some EWS more than two thresholds are used, thus increasing the number of alert levels concerning exceeding different thresholds.

For the EWS to be able to generate a broad set of data related to the triggering indicators, it is also important to increase geographic coverage. In that sense, EWS can be classified into Lo-EWS, and Te-EWS. EWSs dealing with individual landslides at the slope scale can be referred to as local EWSs (Lo-EWSs).

EWSs that operate over large areas on a regional scale are called territorial systems (Te-EWSs). Piciullo *et al.* [35] proposes a model of a Te-EWS as shown in Figure 7 for precipitation-induced landslides. This model complies with the components that an EWS must have risk awareness, monitoring, and warning services, dissemination and communication, and response capability [36].

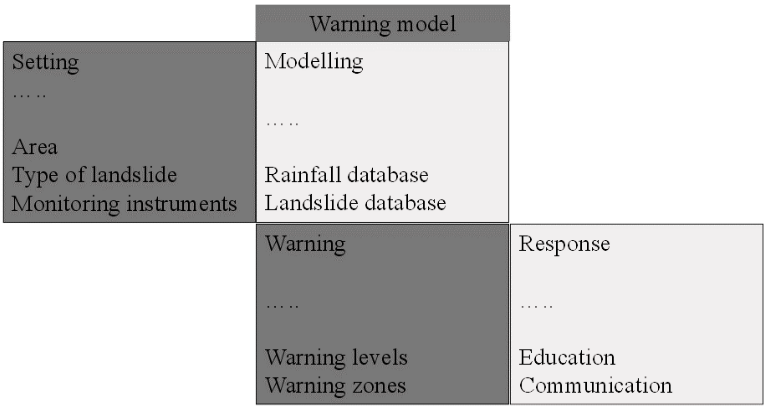

Figure 7. Model of an EWS for precipitation-induced landslides adapted from [35]

In Figure 7, it is possible to observe that the EWS model contains an adjustment module, in which the coverage area is defined, the type of landslide, and the monitoring instruments are established. A modeling module, where precipitation thresholds are defined, generates a set of data associated with precipitation and landslides, obtained from the monitoring instruments of the first module. A third warning module allows the definition of alert levels and danger zones. Finally, a fourth module, which generates the response strategies, is a social aspect module, which includes communication, education, socialization strategies, and everything necessary to reduce the risk of loss of life due to landslides, and to avoid the loss or damage of equipment.

Between the first module of the EWS model proposed in [35] and the first layer of the IoT reference model as shown in Figure 8, proposed by Cisco [19], it is possible to observe a correspondence. The first layer of the IoT model is associated with things, which can be equipped with mandatory communication capabilities and optional detection, actuation, data capture, data storage, and data processing capabilities [37]. This equipment, in the particular case of an EWS and under the model of [35], corresponds to the monitoring instruments as well as to the monitoring and warning services component indicated in [36].

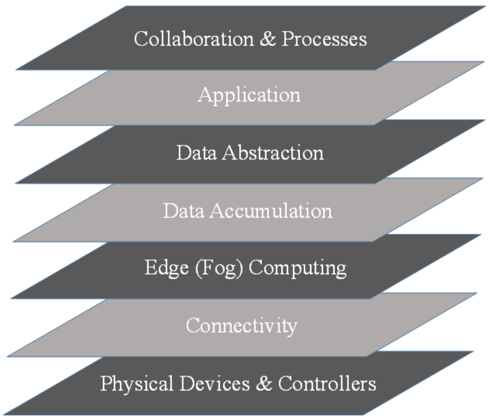

Figure 8. The 7 levels of IoT, image adapted from [19]

Given the correspondence between IoT and EWS models, an EWS is a basic type of data driven IoT system used for environmental disaster risk and impact management. Poslad *et al.* [38] proposed a semantic type IoT-EWS system, in which they enhance the richness of sensor data with the use of lightweight semantics for metadata. On the other hand, Xu *et al.* [39], propose a hierarchical structure for an EWS as shown in Figure 9, to calculate the safety factor of a slope from the processing of the information obtained with a set of sensors.

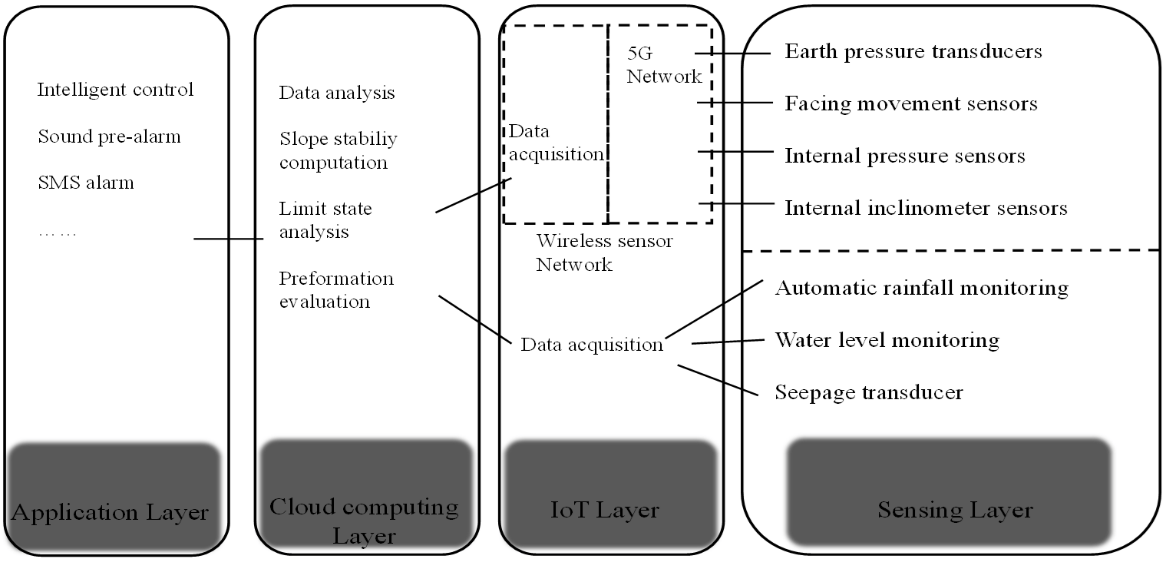

Figure 9. The hierarchical structure of an EWS developed using IoT, adapted from [39]

The hierarchical structure of Figure 9 starts with an application layer in which intelligent controls are generated and messages are issued, i.e., the reporting process is performed, so it is similar to the application layer of the IoT model. Then, there is a cloud computing layer, where data evaluation and analysis are performed, so it brings together the accumulation (storage) and data abstraction layers of the IoT model. Following the previous layer is the IoT layer, where a communication protocol and a data acquisition stage are displayed, as it has a protocol for data transmission, this can be similar to the connectivity layer of the IoT model. Finally, there is the EWS detection layer, which is similar to the layer of things in the IoT model of Figure 8 since this is where the sensors and transducers of different physical variables of the slopes are located.

Finally, considering the above, an interconnection of sensors that records slope and landslide data, which transmits such data to a risk monitoring center, can be considered an IoT application. This application allows addressing the three stages, modules, or technical components of an EWS, which will be reflected in citizen protection against disasters, thus mitigating the loss of lives. In other words, an EWS is a system that makes use of IoT technologies.

4. CONCLUSION

The main objective of this paper was to provide the reader with a review of the scientific publication background of the relationship between IoT and EWS focused on landslides. Therefore, some conclusions were obtained based on the results obtained from the information searches performed. First, while the term IoT has been around since 2002, it is only, until sometime between 2008 and 2009, that it has been used to describe the IoT, where it can be thought of as emerging at the technological level, that is, when it begins to be reflected in various applications in different areas of research. Second, it is possible to visualize that the relationship reflected in scientific production between IoT and EWS focused on landslides begins in 2011, with a significant increase in production since 2016. This year, where the increase begins, coincides with the year in which the scientific production related only to the IoT topic increases. Third, from the review carried out, it can be concluded that the EWS models proposed by different authors correspond to the setting modules and the sensing and IoT layers. In other words, a correspondence between both models is observed, evidencing the relationship between the main topics of this article IoT and EWS focused on landslides. Finally, IoT applied to the development of EWS focused on landslides would greatly help in the investigation and understanding of landslide dynamics, achieving a positive impact on risk mitigation in mountainous cities such as the case of Manizales.

ACKNOWLEDGEMENTS

The authors are grateful to The Universidad Católica de Manizales with the Research Group in Technological and Environmental Developments GIDTA.

REFERENCES

[1] L. E. Tafur and J. V. E. Varón, "Physical, chemical and mineralogical characterization of soils with protective forestry vocation Colombian central andean region," (in Spanish) *Revista Facultad Nacional de Agronomía Medellín*, vol. 67, no. 2, pp. 7335–7343, Jul. 2014, doi: 10.15446/rfnam.v67n2.44176.

[2] A. Calabrese *et al.*, "Systems and alerts for civil protection application: Territorial analysis, scenarios elaboration and fields application through a new technological approach," in *2014 IEEE International Symposium on Innovations in Intelligent Systems and Applications (INISTA) Proceedings*, Jun. 2014, pp. 406–412. doi: 10.1109/INISTA.2014.6873652.

[3] J. A. P. Gómez, F. M. Fernández, and J. Z. Nájera, "Integrated environmental monitoring system of Caldas-SIMAC," (in Spanish) *Boletín Ambient. 145*, Manizales - Caldas, pp. 3–15, Mar. 2018.

[4] Instituto de Estudios Urbanos-IEU, "Manizales, one more tragedy in Colombia," (in Spanish), Manizales, 2018. https://www.institutodeestudiosurbanos.info/manizales-retrato-de-una-tragedia (accessed Sep. 15, 2022).

[5] The Mayor's Office of Manizales, "Studies and designs of risk mitigation works on the hillside of Morro de Sancancio neighboring the Aranjuez neighborhood in the city of Manizales," (in Spanish) The Mayor's Office of Manizales, 2018.

[6] J. A. Pachón-G., "Daily rainfall record and 25-day antecedent rainfall indicators," (in Spanish), Universidad Nacional de Colombia Corpocaldas Alcaldía de Manizales, 2017. Accessed Sep. 15, 2022. [Online]. Available: https://idea.manizales.unal.edu.co/publicaciones/reportes_meteorologicos/red_manizales/niveles_de_alerta/reportes2017/Red%20SAT%20Deslizamientos-Registro%20lluvias%20diarias%20y%20A25%202017.pdf

[7] Miércoles, "Aerial shots of the houses affected by the landslide in Aranjuez," (in Spanish), *La Patria*. 2017. https://www.lapatria.com/manizales/tomas-aereas-de-las-viviendas-afectadas-por-deslizamiento-en-aranjuez-360767 (accessed Sep. 15, 2022).

[8] Sábado, "Requests from the victims have not been resolved after two years of the Aranjuez tragedy," (in Spanish), *La patria*. Manizales, Apr. 2019. https://archivo.lapatria.com/manizales/peticiones-de-los-damnificados-no-han-sido-resueltas-tras-dos-anos-de-la-tragedia-de (accessed Sep. 15, 2022).

[9] O. Husaini and M. Ratnasamy, "An early warning system for active landslides," *Quarterly Journal of Engineering Geology and Hydrogeology*, vol. 34, no. 3, pp. 299–305, Aug. 2001, doi: 10.1144/qjegh.34.3.299.

[10] J. Kaur and K. Kaur, "Internet of things: a review on technologies, architecture, challenges, applications, future trends," *International Journal of Computer Network and Information Security*, vol. 9, no. 4, pp. 57–70, Apr. 2017, doi: 10.5815/ijcnis.2017.04.07.

[11] G. Pecoraro, M. Calvello, and L. Piciullo, "Monitoring strategies for local landslide early warning systems," *Landslides*, vol. 16, no. 2, pp. 213–231, Feb. 2019, doi: 10.1007/s10346-018-1068-z.

[12] M. Esposito, L. Palma, A. Belli, L. Sabbatini, and P. Pierleoni, "Recent advances in internet of things solutions for early warning systems: a review," *Sensors*, vol. 22, no. 6, Mar. 2022, doi: 10.3390/s22062124.

[13] P. K. Hota, B. Subramanian, and G. Narayanamurthy, "Mapping the intellectual structure of social entrepreneurship research: a citation/co-citation analysis," *Journal of Business Ethics*, vol. 166, no. 1, pp. 89–114, Sep. 2020, doi: 10.1007/s10551-019-04129-4.

[14] Y. Ding, R. Rousseau, and D. Wolfram, *Measuring scholarly impact*, 1st ed. Cham: Springer International Publishing, 2014. doi: 10.1007/978-3-319-10377-8.

[15] V. Henao-Céspedes, G. Y. Florez, and Y. A. Garcés-Gómez, "The internet of things in high andean wetland monitoring, historical review approach," *Bulletin of Electrical Engineering and Informatics*, vol. 10, no. 3, pp. 1572–1579, Jun. 2021, doi: 10.11591/eei.v10i3.2653.

[16] D. Evans, "Internet of things. How the next evolution of the internet changes everything," (in Spanish), *CISCO*, 2011. Accessed Sep. 15, 2022. [Online]. Available: https://www.cisco.com/c/dam/en_us/about/ac79/docs/innov/IoT_IBSG_0411FINAL.pdf

[17] I. Lee, "The internet of things (IoT)," *Forbes Magazine*, vol. 169, no. 6, pp. 76–93, 2017, doi: 10.4018/978-1-5225-2104-4.ch004.

[18] N. Gershenfeld, R. Krikorian, and D. Cohen, "The internet of things," *Scientific American*, vol. 291, no. 4, pp. 76–81, Oct. 2004, doi: 10.1038/scientificamerican1004-76.

[19] CISCO, "Internet of things reference model," *CISCO*, pp. 1–12, 2014. Accessed Sep. 15, 2022. [Online]. Available: http://cdn.iotwf.com/resources/71/IoT_Reference_Model_White_Paper_June_4_2014.pdf

[20] OEA, "Manual for the design, installation, operation and maintenance of community systems," (in Spanish), *Organización de los Estados Americanos Manual para el Diseño e Implementación de un Sistema de Unidad de Desarrollo Sostenible y Medio Ambiente*, 2001. Accessed Sep. 15, 2022. [Online]. Available: http://www.oas.org/dsd/publications/unit/oea91s/manual.pdf

[21] S. Lacasse and F. Nadim, "Landslide risk assessment and mitigation strategy," *Landslides-Disaster Risk Reduction*, pp. 31–61, 2014, doi: 10.1201/b15621.

[22] H. Z. Kotta, K. Rantelobo, S. Tena, and G. Klau, "Wireless sensor network for landslide monitoring in Nusa Tenggara Timur," *Telecommunication Computing Electronics and Control (TELKOMNIKA)*, vol. 9, no. 1, Apr. 2011, doi: 10.12928/telkomnika.v9i1.640.

[23] S. Park *et al.*, "A study on the slope failure monitoring of a model slope by the application of a displacement sensor," *Journal of Sensors*, pp. 1–9, Dec. 2019, doi: 10.1155/2019/7570517.

[24] M. T. Abraham, N. Satyam, B. Pradhan, and A. M. Alamri, "IoT-based geotechnical monitoring of unstable slopes for landslide early warning in the darjeeling Himalayas," *Sensors*, vol. 20, no. 9, May 2020, doi: 10.3390/s20092611.

[25] A. Sofwan, Sumardi, M. Ridho, A. Goni, and Najib, "Wireless sensor network design for landslide warning system in IoT architecture," in *2017 4th International Conference on Information Technology, Computer, and Electrical Engineering (ICITACEE)*, Oct. 2017, pp. 280–283. doi: 10.1109/ICITACEE.2017.8257718.

[26] M. Kuradusenge, S. Kumaran, and M. Zennaro, "Rainfall-Induced landslide prediction using machine learning models: the case of ngororero district, Rwanda," *International Journal of Environmental Research and Public Health*, vol. 17, no. 11, Jun. 2020, doi: 10.3390/ijerph17114147.

[27] M. Elmoulat, O. Debauche, S. Mahmoudi, S. A. Mahmoudi, P. Manneback, and F. Lebeau, "Edge computing and artificial intelligence for landslides monitoring," *Procedia Computer Science*, vol. 177, pp. 480–487, 2020, doi: 10.1016/j.procs.2020.10.066.

[28] M. Gamperl, J. Singer, and K. Thuro, "Internet of things geosensor network for cost-effective landslide early warning systems," *Sensors*, vol. 21, no. 8, Apr. 2021, doi: 10.3390/s21082609.
[29] Q.-A. Gian, D.-T. Tran, D.-C. Nguyen, and T. D. Bui, "Flexible configuration of wireless sensor network for monitoring of rainfall-induced landslide," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 12, no. 3, pp. 1030–1036, Dec. 2018, doi: 10.11591/ijeecs.v12.i3.pp1030-1036.
[30] J. Li, C. K. Li, K. Li, and Y. Liu, "Design of landslide monitoring and early warning system based on internet of things," *Applied Mechanics and Materials*, pp. 197–201, Feb. 2014, doi: 10.4028/www.scientific.net/AMM.511-512.197.
[31] M. V. Ramesh, "Design, development, and deployment of a wireless sensor network for detection of landslides," *Ad Hoc Networks*, vol. 13, pp. 2–18, Feb. 2014, doi: 10.1016/j.adhoc.2012.09.002.
[32] L. Zan, G. Latini, E. Piscina, G. Polloni, and P. Baldelli, "Landslides early warning monitoring system," in *IEEE International Geoscience and Remote Sensing Symposium*, 2002, vol. 1, pp. 188–190. doi: 10.1109/IGARSS.2002.1024983.
[33] D. Lagomarsino, S. Segoni, R. Fanti, and F. Catani, "Updating and tuning a regional-scale landslide early warning system," *Landslides*, vol. 10, no. 1, pp. 91–97, Feb. 2013, doi: 10.1007/s10346-012-0376-y.
[34] S. Segoni, L. Piciullo, and S. L. Gariano, "A review of the recent literature on rainfall thresholds for landslide occurrence," *Landslides*, vol. 15, no. 8, pp. 1483–1501, Aug. 2018, doi: 10.1007/s10346-018-0966-4.
[35] L. Piciullo, M. Calvello, and J. M. Cepeda, "Territorial early warning systems for rainfall-induced landslides," *Earth-Science Reviews*, vol. 179, pp. 228–247, Apr. 2018, doi: 10.1016/j.earscirev.2018.02.013.
[36] UNISDR, "Global survey of early warning systems: an assessment of capacities, gaps and opportunities toward building a comprehensive global early warning system for all natural hazards," UN International Strategy for Disaster Reduction (UNISDR), vol. 46, 2006.
[37] ITU-T, "Overview of the Internet of things (ITU-T Y.4000/Y.2060 (06/2012))," (in Spanish), *Unión Internacional de Telecomunicaciones*, pp. 1–20, 2012. http://handle.itu.int/11.1002/1000/11559 (accessed Sep. 15, 2022).
[38] S. Poslad, S. E. Middleton, F. Chaves, R. Tao, O. Necmioglu, and U. Bugel, "A semantic IoT early warning system for natural environment crisis management," *IEEE Transactions on Emerging Topics in Computing*, vol. 3, no. 2, pp. 246–257, Jun. 2015, doi: 10.1109/TETC.2015.2432742.
[39] D.-S. Xu, L.-J. Dong, L. Borana, and H.-B. Liu, "Early-warning system with quasi-distributed fiber optic sensor networks and cloud computing for soil slopes," *IEEE Access*, vol. 5, pp. 25437–25444, 2017, doi: 10.1109/ACCESS.2017.2771494.

BIOGRAPHIES OF AUTHORS

Vladimir Henao Céspedes received his B.S degree in electronic engineering, his M.Sc. degree, and his Ph.D. in engineering from Universidad Nacional de Colombia, Manizales. He currently is an associate professor at the Academic Unit for Training in Natural Sciences and Mathematics, Universidad Católica de Manizales, Manizales. His research interests include electromagnetic compatibility, electromagnetic pollution, lightning discharges, the internet of things, industry 4.0, and remote sensing. He is a member of the Research Group on Technological and Environmental Development GIDTA. He can be contacted at vhenao@ucm.edu.co.

Yeison Alberto Garces-Gómez received his bachelor's degree in Electronic Engineering, and master's degrees and Ph.D. in Engineering from Electrical, Electronic and Computer Engineering Department, Universidad Nacional de Colombia, Manizales, Colombia, in 2009, 2011 and 2015, respectively. He is a full professor at the Academic Unit for Training in Natural Sciences and Mathematics, Universidad Católica de Manizales, and teaches several courses such as Experimental Design, Statistics, Physics. His main research focus is on applied technologies, embedded systems, power electronics, and power quality, and also many other areas of electronics, signal processing, and didactics. He published more than 30 scientific and research publications, among them more than 10 journal papers. He worked as a principal researcher on commercial projects and projects by the Ministry of Science, Tech and Innovation, Republic of Colombia. He can be contacted at ygarces@ucm.edu.co.

María Nancy Marín Olaya is a geologist, M.Sc. (Eng.) in physical instrumentation, M.Sc. (Edu) Education from Diversity, candidate for a Ph.D. competency-based education. Leader of line risk management research of the Group on Technological and Environmental Development GIDTA. Director of the master's degree in global changes and disaster risk of specialization in prevention, attention, and disaster reduction at the Catholic University of Manizales. She can be contacted at mnmarin@ucm.edu.co.