Analysis of the variables that influence the implementation of early warning systems for toxicological emergencies

Raúl José Martelo Gómez[1], Piedad Mary Martelo Gómez[2], Annherys Isabel Paz Marcano[3]

1Specialist in Networks and Telecommunications; Master in Computer Science. Systems Engineer. Tenured Research Professor of the Systems Engineering Program at the Universidadde Cartagena. Leader of the INGESINFO Research Group. Cartagena de Indias, Colombia. Email: rmartelog1@unicartagena.edu.co
[2]Odontologist. Independent researcher. Professor of the Dentistry Program at the Universidad de Cartagena, Colombia. Email: pmartelog@hotmail.com.
[3]Doctor in Administration. Master in Human Resources Management. Professor and researcher at the Universidadde La Guajira Colombia. Email: aipaz@uniguajira.edu.co. AIKA research group.

Received: 13.02.2024 Revised: 25.04.2024 Accepted: 20.05.2024

ABSTRACT
Early warning system alternatives for toxicological emergencies are vital for reducing environmental and public health risks. This exploratory study, using the MICMAC technique, defined and identified the most relevant variables guiding the implementation of early warning systems. After conducting an exhaustive bibliographic review and interviewing experts on the subject, 13 variables were considered relevant and classified according to their impact and dependency. Among the most influential variables were technological infrastructure, cross-sector collaboration, and environmental indicators, while available toxicological data and the regulatory framework were found to be the most dependent. The results reflect the need to strengthen cooperation among key institutional actors, promote technology, and continuously monitor to ensure the operation of early warning systems. This work contributes to the construction of a conceptual framework that contains the systemic dynamics that must be articulated in the design and implementation phases of early warning systems in complex contexts.

Keywords: toxicological emergencies, MICMAC analysis, influence and dependence, risk management, environmental indicators

INTRODUCTION
Globalization and the growing dependency on chemicals in everyday life have given rise to toxicological emergencies that pose a threatening risk to public health and the stability of ecosystems (Xu et al., 2022). An important contribution to this reality is the misuse of chemicals, spills in the industrial field, pollution through water or air, or exposure to toxic agents in the environment, which have increased and have been more reported in developed and non-developed countries (Sharma et al., 2023). In this context, early warning systems (EWS) have become appropriate instruments for the prevention, detection, and management of the risks of toxicological emergencies to provide rapid, coordinated responses with minimal impact on the population and the environment (Van der Oost et al., 2003).
Despite technological and scientific advances, the implementation of these systems faces multiple challenges. It is worth mentioning that factors such as limited infrastructure, limited resources, poor data collection, and a lack of coordination among stakeholders hinder the effective implementation of EWS (Bae & Park, 2014). Therefore, understanding the variables that influence EWS implementation makes sense, as it can contribute to strengthening response capacities in toxicological emergencies and as a means of addressing risk management. The most recent literature on EWS in environmental situations and on toxicological emergencies shows that they are considered preventive tools in critical situations.
As Gamarro and Englander (2023) state, EWS allow for constant monitoring of environmental parameters and the triggering of alerts based on the detection of dangerous levels of contaminants or toxic agents. In this sense, the role that EWS play in the management of toxicological emergencies appears to be important, but their implementation is limited and inefficient in parts of the world where there is high vulnerability as a result of the lack of policies that adequately manage chemical risk (Van der Schalie et al., 2001). Likewise, institutional fragmentation and lack of cooperation between the agencies in charge of toxicological surveillance (Briggs, 2008); and the lack of integration of toxicological and environmental indicators into existing systems (Kleter& Marvin, 2009) hinder the successful implementation of these systems.

EWS rely on technologies such as automated sensors, predictive modeling, and ecological biomarkers, and are capable of providing accurate and timely warnings (Hellou, 2011). However, studies also identify limiting factors in their implementation, such as: a lack of reliable monitoring systems and sensors limits early detection capacity (Huang et al., 2023); effective EWS implementation requires cross-sector collaboration and strong public policies that integrate scientific, governmental, and community actors (Evans-Brown &Sedefov, 2018); developing countries face greater barriers due to a lack of investment in technology and training (Briggs, 2008; Kleter and Marvin et al., 2009); and the use of behavioral and biological biomarkers is a promising tool, but its implementation is still under development in many contexts (Hellou, 2011; Bae & Park, 2014).

The above reflects the need to analyze, in a systematic and structured manner, the variables that influence the implementation of EWS and their relative impact on the system, which can be addressed through analytical methodologies such as MICMAC (Multiplication of Cross-Impacts Matrix Applied to a Classification) (Arcade et al., 2014). The objective of this research is to identify and analyze the variables that determine the application of EWS for toxicological emergencies, using the MICMAC technique.

The justification for this research work responds to the growing need for efficient systems that are useful for the early detection of toxicological emergencies through their prevention and elimination of dangerous situations. By identifying and studying the variables that influence the implementation of these systems, fundamental knowledge will be generated that can be used by environmental administrations and toxicology professionals. This will allow for the promotion of public policies for environmental risk management, the introduction of monitoring technologies and tools for event prediction, and collaboration between the different sectors involved. It will also foster the development of different analytical methodologies that delve deeper into complex systems, such as the MICMAC technique, and will also contribute to providing a solid foundation for future research.

METHODOLOGY

This research work is classified as exploratory and descriptive analysis, and adopts a qualitative approach through a systematic documentary review. This design was chosen because it involves distinguishing and considering the variables that influence the implementation of EWS for toxicological emergencies with evidence collected through a systematic study (Adedoyin, 2020). Exploratory analysis is highly appropriate when there is little information and an initial contact is required to structure the key variables (Reiter, 2017). The qualitative approach focuses specifically on carefully examining the information extracted from the different documents to more effectively understand the relationship between the different study variables (Herrera, 2017).

At the same time, the documentation review enables the evaluation, organization, and synthesis of the extracted information that has to do with studies, reports, regulations, and technical documents concerning the EWS (Van Dinter et al., 2021).

Likewise, this work uses convenience sampling, in turn selecting 12 experts in toxicology, disaster management, public policy, and EWS experts. Data collection is carried out by selecting scientific, technical, and regulatory documents, taking into account the following selection criteria: studies and documents dealing with alert systems and toxicological emergencies; publications corresponding to the last 10 years (2014–2023) in the databases Google Scholar, Scopus, PubMed, and institutional repositories. This process is carried out to ensure that the selected sources have high scientific validity and credibility (Fitzgerald, 2012).

The development of the study consists of the following stages:

1. Document search: Keywords such as "early warning systems", "toxicological emergencies", "implementation variables", and "risk management" were used. The search included scientific literature, technical reports, and related regulations.
2. Selection of documents and experts: The established inclusion and exclusion criteria were applied, and documents were prioritized by reviewing titles, abstracts, and full texts. 12 experts were also selected for their experience, knowledge, and relationship with the EWS.
3. Content analysis: the key variables and factors mentioned in the documents were extracted, and the variables were classified according to their relationship with the implementation of EWS in technological, human, economic, and regulatory factors, among others. In addition, through semi-structured interviews and consultations with experts, the identified variables were validated.
4. Use of the MICMAC technique: The MICMAC technique was applied to weight all variables based on their influence or dependency and classify them into four categories: key, determinant, autonomous, and dependent (Godet & Durance, 2011), for which a calculation software was used. The MICMAC technique is widely used in prospective studies and systems analysis because it allows complex variables to be structured and prioritized for decision-making purposes (Perdomo, 2001).

It should be noted that this study has limitations, such as the fact that the documentary review used is based on preexisting studies and documents, which limits access to primary data. However, the rigorous selection of sources and consultation with experts mitigates this limitation. It is also possible that certain key studies are not freely available online and/or do not meet the inclusion criteria. Similarly, qualitative analysis can be limited by interpretation biases, although the use of software and structured matrices helps to mitigate this limitation.

Despite these limitations, the combination of documentary review and structural analysis using the MICMAC technique provides a clear and rigorous approach.

RESULTS

Below are the results obtained from this research, which focuses on identifying and classifying the most relevant variables that affect the implementation of EWS, using the MICMAC technique and with the collaboration of 12 experts chosen for this purpose.

Based on the literature review, an initial list of 20 variables linked to EWS was constructed. In-depth interviews were then conducted with experts to verify the variables obtained and refine the list, taking into account the relevance of each variable in EWS. A total of 13 variables were selected, which are presented in Table 1. The table has three columns: the first shows a code assigned to each variable to refer to it within the study; the second column contains the variable name; and the third column contains its description.

Table 1. Variables identified through the literature review and expert consultation

Code	Variable Name	Description
V1	Technological infrastructure	Level of development and availability of sensors, monitoring equipment, and analysis software.
V2	Institutional capabilities	Organizational competencies to design, implement, and manage warning systems.
V3	Financial resources	Available budget for technology acquisition, maintenance, and research.
V4	Cross-sector collaboration	Coordination between government entities, NGOs, private companies, and communities.
V5	Available toxicological data	Quality, quantity, and accessibility of information on chemical toxicity.
V6	Regulatory framework	Specific legislation and regulations related to toxicological emergency management.
V7	Staff training	Level of training and specialization of personnel responsible for operating EWS.
V8	Environmental indicators	Environmental variables (water, air, soil) used for monitoring and triggering alerts.
V9	Response time	The speed with which the system detects, processes, and issues an alert in the event of a threat.
V10	Continuous monitoring	Frequency and regularity with which environmental and toxicological conditions are monitored.
V11	Communication networks	Communications infrastructure (internet, radio, SMS) to quickly disseminate alerts.
V12	Integrated risk management	Integration of EWS with other response systems and contingency plans.
V13	Evaluation and updating	The frequency with which the system's effectiveness is evaluated and improvements are made.

Source: Authors

Once the final set of variables was determined, a workshop was held with the experts to analyze and reach a consensus on the level of influence each variable exerts on the others. The experts in this context rated the variables with influences and dependencies, using a scale of 0 to 3. The averages of this rating were used to construct the Cross-Impact Matrix, which represents how the variables influence each other.

The matrix can be seen in Figure 1. An example is that variable V1 (Technological infrastructure) has a strong influence (3) on variable V2 (Institutional capabilities) and a moderate influence (2) on variable V3 (Financial resources), as well as its relationship with variable V4 (Cross-sector collaboration) (2), contrary to variable V13 (Evaluation and updating), where the relationship is weak (1). The matrix in Figure 1 allows for interpreting the interactions between variables at the level of detail shown.

Influence →	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12	V13
V1	0	3	2	2	2	2	2	3	2	2	2	2	1
V2	2	0	1	2	2	2	1	2	1	0	2	1	2
V3	3	2	0	3	2	2	2	2	2	1	1	1	2
V4	3	2	3	0	3	1	2	2	3	1	2	2	2
V5	1	1	2	1	0	2	2	3	1	0	1	1	1
V6	2	2	1	1	3	0	2	1	1	1	1	2	2
V7	3	2	3	2	3	2	0	2	2	0	2	2	2
V8	3	2	2	3	3	2	2	0	2	2	2	2	3
V9	2	2	3	3	2	3	2	2	0	1	2	1	1
V10	3	2	2	2	3	2	1	3	2	0	2	2	2
V11	3	1	2	3	2	1	1	2	3	2	0	1	3
V12	3	0	2	3	3	3	2	2	3	2	2	0	3
V13	1	1	2	2	2	2	1	2	1	1	2	1	0

Figure 1. Cross-impact matrix
Source: Authors

Based on the cross-impact matrix analysis, the influence and dependency indices for each variable were calculated using the specialized MICMAC software. This process allowed the variables to be classified into four categories: determinants, key variables, autonomous variables, and dependent variables. Figure 2 shows this classification represented on the plane of direct influence/dependency, which is divided into four quadrants. The determinant variables, characterized by high influence and low dependency, are located in the upper left quadrant. The key variables, with high influence and high dependency, are located in the upper right quadrant. The autonomous variables, which present low influence and low dependency, are in the lower left quadrant, while the dependent variables, with low influence and high dependency, are located in the lower right quadrant. In this case, as can be seen in Figure 2, the following variables were classified as key variables (upper right quadrant): V1 (Technological infrastructure), V3 (Financial resources), V4 (Cross-sector collaboration), V8 (Environmental indicators), and V9 (Response time); the following variables were classified as determinant or influential variables: V7 (Staff training), V10 (Continuous monitoring), V11 (Communication networks), and V12 (Integrated risk management); only the variable V2 (Institutional capabilities) was classified as autonomous; finally, the following variables were classified as dependent variables: V5 (Available toxicological data), V6 (Regulatory framework), and V13 (Evaluation and updating).

Figure 2. Plane of influence and dependency
Source: Authors

To facilitate the analysis of results, the results of the classification of the variables associated with the implementation of the EWS are presented in Table 2 below.

Table 2. Results of the classification of the variables associated with the implementation of the EWS

Variable Type	Variable	Code
Key Variables	Technological infrastructure	V1
	Financial resources	V3
	Cross-sector collaboration	V4
	Environmental indicators	V8
	Response time	V9
Determinant or Influential Variables	Staff training	V7
	Continuous monitoring	V10
	Communication networks	V11
	Integrated risk management	V12
Autonomous Variables	Institutional capabilities	V2
Dependent Variables	Available toxicological data	V5
	Regulatory framework	V6
	Evaluation and updating	V13

Source: Authors

Calculations performed with MICMAC software using the cross-impact matrix revealed indirect influences, as shown in Figure 3. This graph illustrates how the effects of one variable can propagate through other intermediate variables. That is, a variable may not have a direct influence on another, but may indirectly influence it through a "path" of relationships in the network, which is essential for understanding the dynamics of the entire system and making appropriate decisions. Figure 8 shows the most important indirect relationships, highlighting the most critical ones in red. These occur between variables V1-V12, V5-V8, and V5-V12.

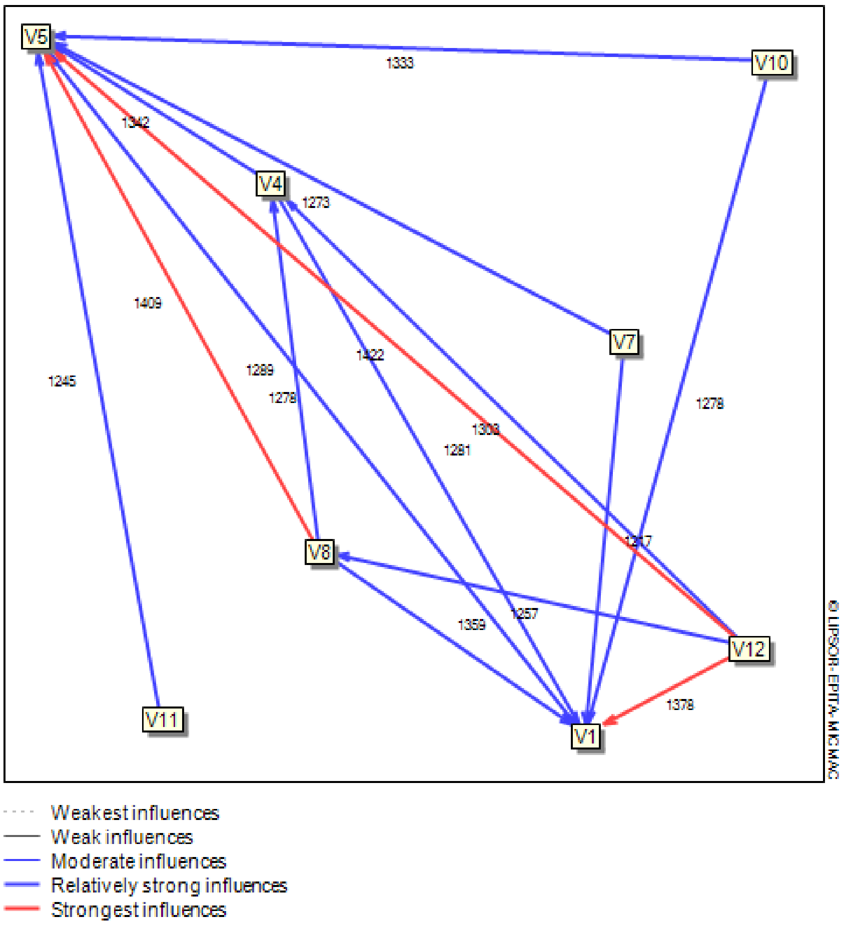

Figure 3. Graph of indirect influences of the variables associated with the implementation of the EWS
Source: Authors

Analysis and discussion of results

The results show that technological infrastructure, financial resources, cross-sector collaboration, environmental indicators, and response time are essential elements for the success of EWS. This is consistent with the technical and collaborative nature of these systems. Technological infrastructure is a key driver that enables the successful implementation of sensors, monitoring systems, and predictive analysis, while cross-sector collaboration ensures that government, private, and community actors demonstrate the willingness to make the necessary decisions in a coordinated manner in toxicological emergencies.

Furthermore, the classification of environmental indicators and response time as key variables demonstrates the constant need to continuously monitor critical environmental conditions and implement rapid risk responses. This makes EWS not only capable of responding to emergencies, but also play a role as predictive systems.

On the other hand, the placement of both the available toxicological data and the existence of a regulatory framework as dependent variables indicates an area for improvement. Although these variables are important, they go hand in hand with other system factors such as technological infrastructure and staff training. This leads to the conclusion that EWS cannot operate effectively without updated databases and a legal framework to support them. Finally, the discovery of indirect influences between variables such as technological infrastructure and integrated risk management demonstrates the importance of developing strategies based on direct interactions, but also on second-order effects within the system.

The results obtained are in line with those of the researchers, but at the same time, they reveal new insights; for example, the analysis by Bae and Park (2014) as well as that of Hellou (2011) highlighted the role of sensors and predictability tools as a necessary object of continuous monitoring. This study reinforces that conclusion but also places monitoring as a determinant variable, in direct interaction with cross-sector collaboration and environmental indicators. For their part, Evans-Brown and Sedefov (2018) included collaboration as a key element for the management of emerging chemical risks. The results of this study reinforce the previous ones, showing how cross-sector collaboration is revealed as a central variable not only for the implementation of EWS but also enables their interaction with risk management systems.

In turn, these findings also extend the study by Kleter et al. (2009), which highlighted the dependency of toxicological data on policy and funding. Here, it is evident that these variables, although critical, are influenced by the broader systemic environment.

As noted, the MICMAC approach has been demonstrated as a method that allows for examining the complexities of EWS, making visible all those interactions that are not clearly perceptible in the traditional approach. This research provides a robust framework for the analysis of complex systems that can be used in toxicological emergencies, as well as in other fields related to risk management. The positioning of variables such as technological infrastructure (V1) and integrated risk management (V12) in positions of influence reinforces theories that highlight the need for integrated systems to address global risks.

The results not only suggest, as practical implications, that investing in advanced technology can not only improve detection and response, but also increase the effectiveness of other variables such as collaboration and environmental indicators. Furthermore, despite being dependent, this variable is a priority, since a clear and up-to-date legal framework not only provides legitimacy but also institutional support in the case of EWS. Furthermore, it is necessary to strengthen networks between the public-private-community sectors to optimize resource allocation and the implementation of joint protocols.

Regarding recommendations for further research, as shown by the results, it would be interesting to highlight very important indirect relationships, such as those in V1-V12. Further research could model how these relationships change across different scenarios, using dynamic simulation or Bayesian networks, and also consider how influence-dependency dynamics would change in urban, rural, or contexts with different levels of economic development. Furthermore, variables linked to social perception or social behavior could be included, which could reveal additional barriers and opportunities for EWS implementation. Finally, it would be possible to evaluate how investments in infrastructure or technology translate into operational benefits in risk mitigation or increased resilience in EWS.

CONCLUSIONS

This paper investigated the importance of variables influencing the implementation of EWS in toxicological emergencies using the MICMAC technique. This approach aims to understand the direct interactions and indirect influences that describe the more complex relationships within the system and how they develop. The results and conclusions presented here are the most significant considerations based on the variables studied.

Technological infrastructure (V1) was the most influential variable in the EWS, highlighting the need for investments in sensors, digital platforms, and predictive tools for early detection of emergencies. Cross-sector collaboration (V4) is key to optimizing resources in responding to situations of this type, while environmental indicators (V8) and continuous monitoring (V10) were necessary conditions for preparing assessments and triggering alerts at the right time. Despite being dependent variables, toxicological data (V5) and the regulatory framework (V6) emerged as pillars that need to be reinforced through reliable databases and clear regulations.

Indirect influences, such as the link between V1 and integrated risk management (V12), highlight the need to consider EWS from a systemic perspective.

The MICMAC technique allowed these dynamics to be mapped, providing a replicable approach to risk management. Establishing periodic evaluation and updating mechanisms (V13) and exploring new variables, such as community perception and financial sustainability, are essential to improving the implementation of EWS in different contexts.

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