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Intentional radiological exposure scenario evaluation by comparisons based on computer simulation

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Abstract: Nuclear or radiological mass incidents represent a threat that requires sophisticated coping strategies. This study aims to contribute by presenting a dual computational modeling methodology that juxtaposes numerical and analytical models to address a specific radioactive release scenario. This methodology seeks to extend beyond the theory underlying the modeling processes, favoring decision-making, especially in the early stages of such confrontation. This investigation applied a dual-model structure based on numerical methods and analytical techniques to simulate a radiological scenario promoted by activating a radiological dispersal device (RDD). It is important to emphasize that this methodology is not limited to RDD scenarios and is being proposed for application to any external release of radioactive materials. By evaluating and comparing the results of the simulations, particularly in areas close to the release point and in shorter time intervals, it is possible to verify the most appropriate model and identify scenarios in which the two models produce convergent results. The findings highlight the importance of estimating radiation doses, suggesting that such estimates can influence the understanding of radiological risks and their dependence on local atmospheric conditions. Careful interpretation and application of such results can mitigate epidemiological risks, enhance coordination capabilities, and stimulate the development of strategic responses.

Keywords: computational simulation, urban radiation release, support to decision, critical infrastructure disruption

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Avaliação de cenário de exposição radiológica intencional por comparações baseadas em simulação computacional

Resumo: Incidentes nucleares ou radiológicos de massa representam uma ameaça que necessita da implementação de estratégias de enfrentamento sofisticadas. Este estudo visa contribuir apresentando metodologia de modelagem computacional dupla que justapõe modelos numéricos e analíticos para abordar um cenário específico de liberação radioativa. Tal metodologia busca se estender além da teoria subjacente aos processos de modelagem, favorecendo a tomada de decisão sobretudo no estágio inicial de tal enfrentamento. Nesta investigação, foi aplicada uma estrutura de modelo duplo baseada em métodos numéricos e em técnicas analíticas para simular um cenário radiológico promovido pela ativação de um dispositivo de dispersão radiológica (RDD, do inglês). É importante ressaltar que esta metodologia não se limita a cenários RDD, sendo proposta para aplicação a qualquer liberação externa de materiais radioativos. Ao avaliar e comparar os resultados das simulações, particularmente em áreas próximas ao ponto de liberação e em intervalos de tempo mais curtos, é possível verificar o modelo mais adequado bem como a identificação de cenários nos quais os dois modelos produzem resultados convergentes. Os achados ressaltam a importância de estimar as doses de radiação, sugerindo que tais estimativas podem influenciar a compreensão dos riscos radiológicos e sua dependência com relação às condições atmosféricas locais. A interpretação e aplicação cuidadosas de tais resultados têm o potencial de mitigar riscos epidemiológicos, aprimorar as capacidades de coordenação e estimular o desenvolvimento de respostas estratégicas.

Palavras-chave: simulação computacional, liberação de radiação, suporte à decisão, infraestrutura crítica

1. INTRODUCTION

Urban areas face many challenges, including various disasters that can directly impact critical infrastructure. Among these, radiological contamination from a radiological dispersal device (RDD) is potentially the most disruptive [1]. ARDD is a device that combines particulate radioactive material and a dispersion mechanism, which can be exclusively mechanical or rely on propulsion provided by explosive materials [1]. The triggering event of a RDD presents one of the most complex challenges in protecting the critical infrastructure of an inhabited urban area due to the lack of accurate information or the inability to collect it in real-time [2, 3]. To effectively respond to such a crisis, specific information is essential, including the location and type of the event, dose profile, dispersal characteristics, expected contamination, population density in the area, local weather conditions, forecasts for the upcoming days, available infrastructure for support, and other relevant details. A lack of access to this information can present a predictable obstacle during the initial response to the crisis.

The study focuses on releasing radioactive material, whether intentionally or not, over an urban area. While there are references in the literature to using the HotSpot code and numerical modeling for the dispersion of radioactive material, comparative studies that focus on the connection between the models for complementary applications are not commonly found. Additionally, the initial hours of a radiological dispersion event may be considered the most complex for decision-making, mainly due to the lack of accurate information about the release characteristics. The proposed study offers much-needed support for decision-making in these critical hours with its conservative simulations that exaggerate the event. This study considers the RDD activation in an urban area, and computational simulations are carried out to assess the immediate threat represented by the environmental radiation doses imposed by the mechanical dispersion of radioactive material (Cs-137). Such simulations are not intended to replace actual data. On the contrary, they are predictions and have the general objective of serving as a basis for preparing a response to possible future scenarios. However, predictive capacity can assess threats simultaneously with an actual event in its initial phase. Two different models were used to carry out the simulations. A numerical and an analytical model are used to simulate the same situation, and the data are compared with each other, seeking to take advantage of what best describes each one in each slice of the event. This practice aims to optimize computational tools and increase the chances of results having real applicability for decision support, including recommendations for evacuation, shelter, or staying in safe areas, especially in this study's initial phase, considering the first 4 days.

2. MATERIALS AND METHODS

This study compares two distinct methodologies used to model the dispersion of Cs-137, employing analytical and numerical approaches. An open, unobstructed terrain was chosen for a conservative evaluation, aiming to provide a clearer insight into the mechanisms and phenomena associated with the uncontrolled release of radioactive material into the atmosphere while minimizing the influence of additional variables related to physical obstacles. Simplifying the scenario to a terrain without buildings makes it possible to conduct a direct evaluation in a controlled environment. This methodology also enables the quantification of meteorological aspects that impact dispersion, which in this study are classified according to Pasquill-Gifford (PG) classes [4]. In actual scenarios, the dispersion of contaminants in urban areas may be markedly affected by the presence of buildings and their intricate topography. Modeling for such scenarios may necessitate using Computational Fluid Dynamics (CFD) methods, which can accurately capture the detailed effects of urban structures on contaminant dispersion. Previous studies [5] show that while CFD can be applied in complex urban conditions, software availability and processing time limit its suitability for this work.

Even in a simplified scenario suitable for rapid action, this study provides strong support through the combined use of analytical and numerical methods [6, 7]. These approaches are effectively applied in different response and recovery phases in dealing with disruptive events, serving as a valuable tool for both rapid preliminary assessments and detailed medium- and long-term studies [7]. Consequently, further research will enable the modeling of complex urban scenarios, utilizing CFD or another more suitable model to consider the effects of buildings and structures in a more immediate and less geometrically biased perspective. These advancements may lead to more accurate and detailed approximations of the dispersion of radioactive material in urban environments.

This research utilized two simulation software tools: ANSYS – CFD [8], which employs a numerical approach, and HotSpot Health Physics codes [9], which performs analytical simulations. Both models utilized PUFF-type dispersion simulation without the use of explosives. In the analytical model simulated with HotSpot, this function is activated by the general plume simulation mode option. The results of the analytical simulation were compared to those obtained by numerical simulation to evaluate the consequences of adopting different mathematical models considering the behavior of the distribution of radioactive material and, consequently, the total effective dose equivalent (TEDE) over the initial 4 days. The TEDE is defined as the sum of the effective dose equivalent (external exposure) (EDE) and the committed effective dose equivalent (internal exposure) (CEDE), as defined by the US Nuclear Regulatory Commission (NRC) and the International Commission on Radiological Protection (ICRP) [10]. TEDE estimates radiation dose, forming the basis for determining stochastic and deterministic effects. However, it does not directly represent the source of potential biological damage, as this depends on various specific biological parameters that collectively produce a biological effect.

Analytical methods involve using traditional functions from trigonometry, statistics, calculus, and differential equations to find symbolic representations of solutions. While a computer can be used for specific calculations, the actual solution work is done through analysis. On the other hand, numerical methods involve integrating a differential equation numerically step by step, resulting in a numerical solution. In this case, no analytical function is identified with the solution.

Although the concept of TEDE and its estimated values may be insufficient to determine consequences, TEDE was chosen as a parameter for discussion because it represents the origin of any possible biological damage to living objects. The TEDE is the basis for several epidemiological models that estimate radiological risk within populations [10-12]. Its implications for individual and collective health depend on age, sex, genetic predisposition, and epidemiological incidence factors of relatable diseases.

Both the analytical and the numerical methods have their advantages and disadvantages. The exact process applied to a situation may yield different results based on the assumptions made during the model setting. It is important to note that this study does not aim to compare the results obtained by applying different methods to the same problem. Instead, the study examines the applicability of various methodological approaches in the initial phase of an event (approximately 96 hours), emphasizing characteristics that may justify the preference for one method over another, mainly when dealing with short distances from the release point. The study assumes that all hazards are assessed based on the local radiation doses and dose rates. Therefore, the analytical and numerical model comparisons focused on evaluating this key variable.

In the analytical simulations (Gaussian model), we accounted for uncertainties by considering the radioactive contamination plume's standard deviations (lateral and vertical). In the case of numerical simulations, we chose not to include these uncertainties due to the discretization schemes adopted. These schemes helped control truncation and rounding errors in numerical methods for differential equations, enhancing precision and reducing uncertainties. The same scenario and conditions were replicated in both analytical and numerical analyses. The initial approach is commonly employed in dispersion studies and, in this work, enables the assessment of Cs-137 (or the relevant radioactive element) concentration evolution downwind immediately following release under diverse meteorological conditions. Furthermore, we considered the PG classes [1] to conduct the simulations, which estimate the degree of atmospheric turbulence encountered. The classes range from A (extremely unstable) to F (extremely stable) and are crucial for simulating the spread of radioactive substances. They help classify atmospheric stability conditions that affect the radioactive plume's characteristics.

2.1. Computational Simulation I: Analytical

The analytical simulation was conducted using HotSpot Health Physics Codes version 3.1.2, a software developed by the National Atmospheric Release Advisory Center (NARAC) at the Lawrence Livermore National Laboratory (LLNL) in the United States [9]. This software employs a semi-empirical Gaussian model to estimate the dispersion of radioactive materials as they are carried by the wind over the affected area. Designed to aid emergency response personnel and planners, HotSpot facilitates the assessment of incidents involving radioactive materials. It utilizes a conservative model to calculate the dose and concentration of radionuclides resulting from atmospheric releases.

The hypothetical RDD used Cs-137 as a source with a maximum activity of 4.44E+14 Bq (1.2E+04 Ci), typical of sterilization facilities [13]. The activity of the Cs-137 source was employed as a reference point for the simulated scenario, without any intention of establishing a direct connection to sterilization facilities or the original encapsulation methods for the material. The simulation considers the possible existence of this activity level across several contexts, including materials that may be reconfigured, remain unprotected, or be remobilized, regardless of their specific origin. The half-life of Cs-137 is approximately 30 years, much longer than the 4-day simulation period. Therefore, we can neglect the correction in TEDE due to radioactive decay. The study employed a comprehensive approach to the complete vaporization of the source term, effectively rendering the radiation doses attributed to the ballistic effects of any resulting fragments negligible. Consequently, key parameters such as damage rate (DR), airborne release fraction (ARF), respirable fraction

(RF), and leak path factor (LPF) were conservatively assigned a value of unity (1). This assumption implies that the radioactive material was wholly released as aerosol particulates. Furthermore, an average wind speed of 3 m/s, representative of typical conditions across various performance grades, was utilized, encompassing all classes from A to F. The effective release height (H_{eff}) was established at 10 meters above ground level, reflecting the average elevation of most chimneys emitting smoke, as Homann [9] characterized.

For the calculations, large metropolitan areas typically show lower radiation doses than standard terrain (open field). This is due to increased plume dispersion caused by turbulence from larger building structures [6, 9]. The metropolitan area factor considers the enhanced dispersion of plumes from densely packed structures and the heat retention properties of urban surfaces like asphalt and concrete [6]. Individuals within an environmental radiation field are subjected to different levels of TEDE [10] as the radioactive plume travels. The analytical method has limitations that must be considered, such as its uncertainties and the 10 km limit imposed for more accurate assessments. The second limitation concerns the urban geometry in the simulations, leading to overestimated results. The Gaussian model for the contamination plume from the HotSpot is given by Equation (1) [9].

$$C(x,y,z,H) = \left(\frac{Q}{2\pi\sigma_y\sigma_z u}\right) exp\left[-0.5\left(\frac{y}{\sigma_y}\right)^2\right]\left\{exp\left[-0.5\left(\frac{z-H}{\sigma_z}\right)^2\right] + exp\left[-0.5\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\} exp\left[-\frac{\lambda x}{u}\right] DF(x) \quad (1)$$

where C, Q, H, and λ are, respectively, the result of the integration of the atmospheric concentration (Ci-s.(m^{-3}), the source-term (Ci), the effective release height (m), and the radioactive decay constant (s^{-1}). The downwind, crosswind, and vertical axis distances (m) are represented by the coordinates x, y, and z, respectively. The variables σ_y and σ_z represent the concentration distribution's standard deviation (m) in the transversal and vertical wind directions. The variable *u* is the mean wind velocity at a specific release height (m.s^{-1}), and DF(x) is the dimensionless plume depletion factor.

2.2. Computational Simulation II: Numerical

While the analytical dispersion model focuses on solving the diffusion-advection equation, the numerical model incorporates the atmospheric air velocity field to study the transportation of radionuclides in the atmosphere. To achieve this, a numerical atmospheric dispersion simulation was conducted using CFD techniques, precisely the Eulerian method. This method accounted for a multiphase flow between Cs-137 particulate and atmospheric air, which was diluted and coupled.

CFD supports the numerical modeling of the atmospheric dispersion. The ANSYS-CFD software discretizes atmospheric flow equations using the Finite Volume method, creating a system of algebraic and linear equations. This tool handles pre-processing, processing, and post-processing steps for simulations. The Space Claim software was used to design the geometry, with Meshing generating 7.61E+04 Nodes and 3.99E+06 Elements of structured meshes measuring 1 m x 1 m. The solver was ANSYS CFX, with the SIMPLE algorithm for pressure-velocity coupling. CFD-Post analyzed the results obtained through the iterative solving of the algebraic equations using the Gauss-Seidel method [14] and a convergence criterion 1.0E-04. To account for radioactive decay, an algebraic expression was formulated in CFX-Pre to convert density in $kg.m^{-3}$ to $Bq.m^{-3}$ based on the activity of Cs-137 in the atmosphere. A conversion formula was also devised to calculate the TEDE in sieverts (Sv) based on the concentration (C) in $Bq.m^{-3}$. This was done using the methodology outlined in the Federal Guidance Report 11 (FGR 11) to determine the radiation dose resulting from simulated levels of Cs-137 exposure for individuals remaining in the exact location and exposed in the direction of the wind. Our research group conducted a similar simulation, described in greater detail by Curzio and colleagues [15, 16].

The equations that regulate flow in the Eulerian method rely on the Reynolds-averaged Navier Stokes (RANS) model, as established by Chen and colleagues [17] and Stockie [18]. To account for the dispersed phase of particulate Cs-137, the diffusion-advection theory was employed, utilizing an analytical model with the turbulent diffusive transport coefficient (K^t)

determined by the Kolmogorov and Schmidt relation, as shown by Equation 2, as per Rabi and colleagues' findings [19].

$$K^t = \frac{\mu^t}{\rho Sc^t} \tag{2}$$

where μt is the turbulent dynamic viscosity, ϱ is the fluid density, and Sct is the turbulent Schmidt number (0.5 ≤ Sct ≤1.00).

In this study, the Sc^t parameter has been established at 0.7, and the *k-ε* turbulence model has been utilized to represent turbulent viscosity μ^t. This model has demonstrated favorable outcomes for several atmospheric flows, mainly when hindrances downstream of the source term are not considered.

Table 1 has been included to compare the simulations. It summarizes the initial conditions utilized in both the analytical and numerical models. This table encompasses key meteorological parameters, characteristics related to releasing radioactive material, and considerations concerning the affected urban environment.

Table 1 - Comparison of parameters used in analytical (HotSpot) and numerical (CFD – ANSYS) simulations.

Parameter	Analytical Simulation (HotSpot)	Numerical Simulation (CFD - ANSYS)
Radionuclide	Cs-137	Cs-137
Activity	4.44E+14 Bq	4.44E+14 Bq
Release	Instantaneous	Instantaneous
Released Height	10 m	10 m
Wind Speed	3 m/s	3 m/s
Model type	Semiempirical Gaussian	Eulerian – Finite Volume Method
Atmospheric stability	Classes A to F considered	Implicit via (k–ε) turbulence model
Aerosol assumption (ARF, RF, etc.)	Full aerosolization assumed	Explicitly modeled in multiphase flow
Decay consideration	Disregarded (short simulation period)	Included via algebraic equation

In conclusion, the conversion of concentration (C) expressed in Bq·m^{-3} to the radiation dose (TEDE, measured in Sv) was conducted utilizing Equations 3 and 4 as outlined by Eckerman et al. (1988). C_0 represents a conversion factor translating measurements from mass density (kg/m^3) to activity concentration (Bq/m^3) in radioactive materials.

$$C = \frac{C_0}{1.34} A e^{-\lambda\left(\frac{x}{U}\right)} \quad (3)$$

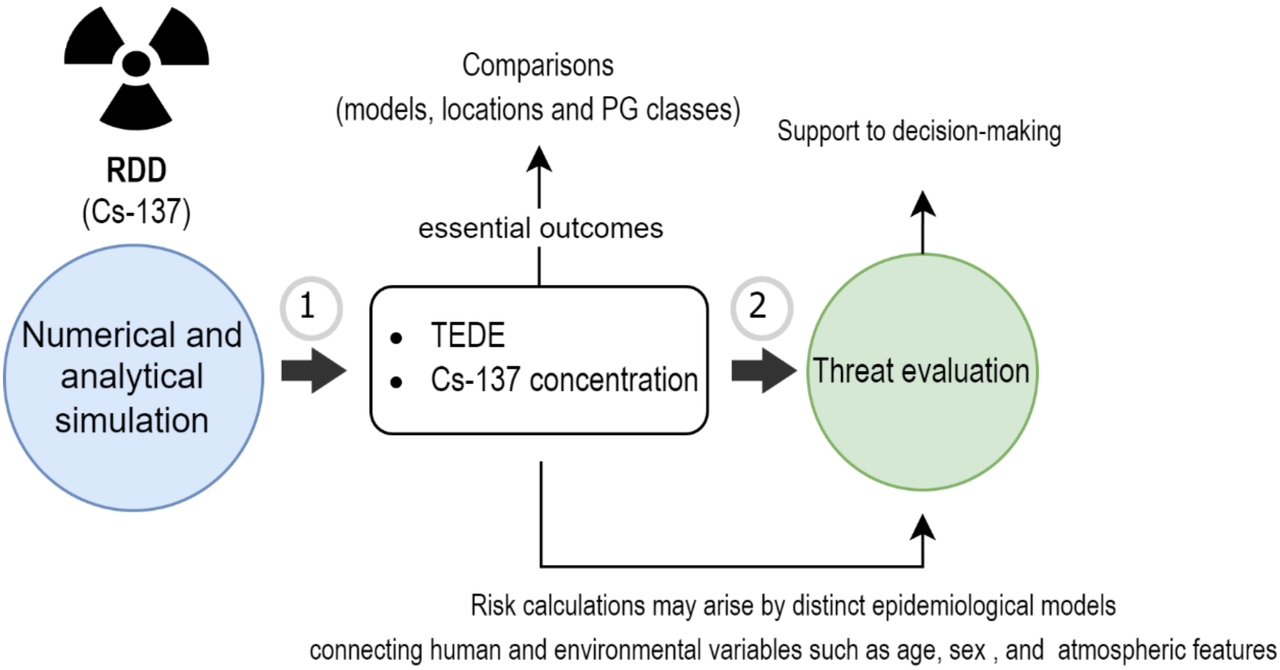
$$CTEDE = f \quad (4)$$

where f [Sv.kg^{-1}.m^{-3}] is the concentration-to-dose conversion factor, tabulated in FGR 11 according to the radionuclide used. [20].

2.3. Statistical evaluation

The Brown-Forsythe test is a statistical approach that can determine whether the variance across multiple groups is similar [21]. To conduct this test, the mean of each column is subtracted from the corresponding values in a data table, and the absolute value of the difference is calculated. The resulting values are then subjected to One-way ANOVA, and the P-value generated is reported as the Brown-Forsythe test result. This test is crucial in ensuring that the only factor that sets apart the groups under study is their variability. Scientists often utilize the Brown-Forsythe test to verify that the distribution of radioactive material in space follows a Gaussian distribution. Although interactions between TEDE values and exogenous variables could potentially lead to non-Gaussian results, the Brown-Forsythe test helps researchers take extra precautions. Obtaining a non-significant outcome ($P > 0.05$) through this test assures that variability remains uniform even after data interaction and the Gaussian distribution. The Brown-Forsythe test ensures that statistical analysis is accurate and reliable, mainly when working with intricate data sets. The test was employed separately for numerical and analytical sets, and the outcomes revealed that the only factor that sets apart the groups under study is their variability. Figure 1 presents a general summary of the methodology applied to the study.

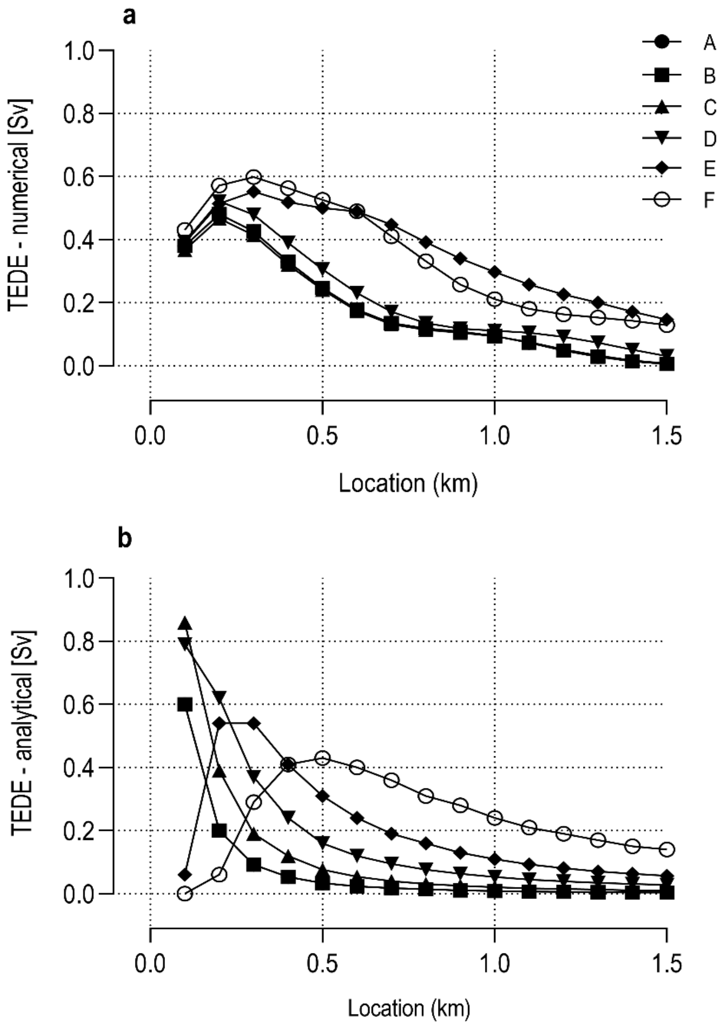
Figure 1: General methodology scheme.



3. RESULTS AND DISCUSSION

Figure 2 shows the TEDE estimation beyond 0.1 km from the release point of Cs-137 in an urban environment due to lower values expected for locations closer than 100 m to the release point. The TEDE is essential for assessing radiation risks and public health impact. Figure 2a displays numerical simulation data, while Figure 2b shows the analytical approach. This data is necessary for estimating risks and developing effective mitigation strategies for such events.

Figure 2: Numerical (2a) and analytical (2b) estimates for TEDE as a function of distance from the triggering site and the Pasquill-Gifford (PG) stability classes (A to F).

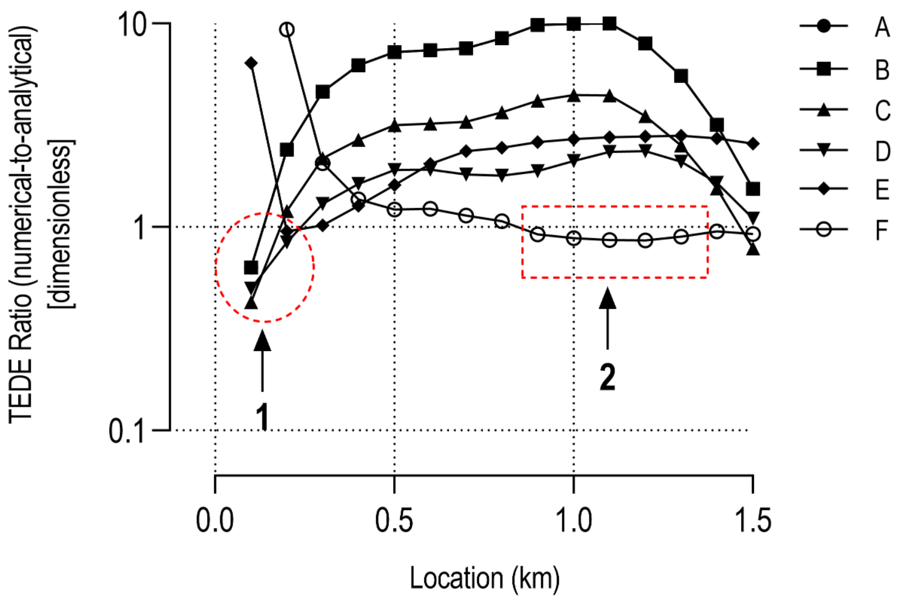


The TEDE profile in Figure 2a appears smoother overall compared to the analytical one. As the locations get closer to the release site, the differences between the analytical and numerical approaches become more prominent. However, upon a thorough analysis of the data, it is evident that the numerical model converges to typical values in these locations, suggesting a reduced sensitivity to variations in local atmospheric stability (PG classes). It is important to clarify that PG Class A is not included in the figures, as the initial parameters used in the simulation result in outcomes consistent with those of PG Class B. Although these classes are conceptually distinct within the Pasquill-Gifford framework, their values can yield identical results under certain parameter conditions. While this approach is beyond the scope of this study, a comprehensive discussion of the phenomenology related to PG classes can be found in references [4, 6]. In contrast, the analytical model exhibits high sensitivity to PG classes at the exact locations. The findings suggest that the numerical model underestimates TEDE values, especially in the stages closest to the emission source. This might happen due to the isotropy condition of the intrinsic turbulence model, promoting the plume diffusion under the same magnitude in all directions. At the same time, the Gaussian model is heavily influenced by the advection effect at these initial stages, justifying the TEDE values obtained by this model under the conditions mentioned above. It is recommended that immediate safety measures from a conservative perspective use analytical data as support, particularly for locations within 0.5 km. These measures do not refer to quick post-event actions, as they involve unpredictable demands in the initial operational environment. Additionally, the time it takes to execute these tasks may not allow local meteorological reviews to support decision-making. This study's methodology may improve prediction capabilities for public protection. It provides a basis for developing emergency action strategies, identifying vulnerabilities, and potentially maximizing infrastructure resilience.

The comparison of results in Figures 2a and 2b may be insightful. Although the general behavior is similar, intrinsic differences exist between the numerical and analytical approaches. Examination of PG classes E and F reveals that the numerical approach yields almost equivalent consequences for the event, with a slight change between them. The TEDE for PG class F exhibits greater relevance in areas closer to releasing radioactive material. The numerical equivalence point for PG classes E and F occurs in the numerical modeling for location 0.6 km, marking the alternation point for the classes, which will likely return to equivalence after 1.5 km. Compared to the analytical approach, the same phenomenon is verified by the modeling and results presented in Figure 2b. Intense transients are observed, in addition to the inversion of trends. Unlike the numerical simulation, the analytical results show that the preference for close points is PG class E. When comparing the results from Figures 2a and 2b, the expectations for PG class F are practically the same, while PG class E experiences fluctuations to some extent.

Figure 3 presents the results of direct comparisons between numerically and analytically simulated results for TEDE. The ratio between the data was calculated for point-by-point comparison considering the location and PG classes. The ratio was taken in the numerical/analytical sense, and once unity is reached, it is clear that the simulated data are equivalent under these conditions.

Figure 3: Comparisons between numerically and analytically simulated data ratios (TEDE).



After analyzing the TEDE ratio results in Figure 3, it has been confirmed that PG classes A to E are better suited for analytical modeling, especially when the distance from the release point is more significant than 0.5 km. However, PG class C performs better in analytical modeling for the 1.5 km location. This could be because PG class C is more neutral, resulting in lower turbulence values in numerical modeling and better results in analytical modeling.

The PG classes A and B exhibit similar atmospheric characteristics, significantly overlapping their graphical representations. This similarity creates a challenge in distinguishing the dispersion values associated with these classes, as illustrated in Figures 2 and 3. Consequently, the results may become nearly indistinguishable at specific analysis points within atmospheric dispersion simulations. This overlap indicates moderate to high instability in both classes, complicating result differentiation during analysis. Figure 3 highlights two regions of interest: Region 1, near the RDD trigger point, where PG classes B to D denote more conservative values in analytical simulations, and Region 2, between 0.8 and 1.3 km from the release point, where PG class F provides the most relevant analytical result. For locations closer to 1.5 km, the ratio for PG class F tends to equalize numerical and analytical calculation modes. It should also be noted that as the distance from the release point increases, the simulation models tend to converge toward each other, except for PG class E. The analytical model offers a more conservative approach to immediate response requirements after a radiological or nuclear event, providing prompt estimates essential for initial decision-making. This model prioritizes speed and simplicity, which are critical when accurate data is unavailable. On the other hand, the numerical model involves more complex variables and is better suited for detailed post-event analysis. It provides greater accuracy and is particularly valuable for retrospective assessments where time sensitivity is less critical. This distinction highlights the unique strengths of each model, supporting the use of the analytical model for rapid, conservative estimates and the numerical model for in-depth analysis as more data becomes available.

Upon careful evaluation of the results, verifying their implications for a region affected by a disaster is possible. Modeling can sometimes present opposing results, so the ratio between the results may help determine the most appropriate model. Practical conditions must also be considered when making decisions, which are often absent in the initial response to a catastrophic event. To minimize risk, it is essential to identify high-risk locations, propose evacuation routes, and assess critical infrastructure vulnerabilities in advance.

The findings of this study suggest that slightly unstable atmospheric conditions, such as those associated with the PG class C, may enhance the transport of radioactive material, leading to an increased dispersion. In such situations, the atmospheric flow can carry radioactive material from the emission source to distant regions, reducing concentrations in nearby areas. The findings suggest that these conditions are most prominent under the influence of the PG class C. Additionally, these atmospheric conditions can lead to increased vertical mixing, facilitating the dispersion of radionuclides at different altitudes and promoting a more uniform distribution of radioactive contaminants, thus preventing localized accumulations [7]. Furthermore, scattered clouds, characteristic of the PG class C, may intensify atmospheric turbulence, significantly mixing radioactive material with other atmospheric aerosols. Ultimately, this process may result in decreased concentrations of radioactive material near the surface, particularly in urban environments [6], simplifying the modeling of uncontrolled emissions of radioactive material into the urban environment.

The lack of non-convergence observed in the PG class E may be attributed to the unique atmospheric characteristics identified within this category. In cases of heightened atmospheric stability, vertical air movement is constrained, posing challenges for accurate numerical modeling of substance dispersion. Under these conditions, numerical methods may find difficulties in estimating airflow patterns, particularly in zones near the ground. Additionally, the level of atmospheric stability typical of PG class E tends to decrease turbulence, a significant factor in the dispersion of radioactive materials. The *k*-epsilon turbulence model utilized in this study is based on the assumption of isotropic atmospheric flow [7]. However, this approach may not be entirely suitable for capturing the complexity of the atmosphere in such conditions, encountering an anisotropic dispersion environment under varying turbulence patterns in different directions and altitudes [6]. Although sufficient for a conservative approach, the proposed numerical model may not have accurately replicated the influence of these turbulence patterns and their effects on atmospheric dispersion, indicating the necessity for more realistic investigations in future studies. Advanced models such as the *Large Eddy Simulation* (LES) model, which directly addresses larger turbulent scales or more intricate turbulence models, may provide a better solution.

The hybrid evaluation method can be used immediately after a radiological or nuclear event. Still, its simulation results are only helpful for initial decision-making when accurate information is unavailable. Instead, this methodology should be used for forecasting and responsive to the Agency's readiness improvement. This could provide valuable insights for an organized urban society to utilize its resources better. The hybrid evaluation method is suitable for prompt application following a radiological or nuclear incident. However, its simulated outcomes should only guide preliminary decision-making when precise data is unavailable. Instead, it is imperative to employ this approach for forecasting and long-term preparedness. An orderly urban community can gain advantageous perspectives and optimize resource allocation.

As with any methodology for dealing with disruptive situations in urban regions, some limitations must be addressed. The primary limitation is fundamental: although scientifically supported, the models are not reality but only a representation. This impacts the object of study represented in the threat (TEDE), which emerges from a disruptive situation in an inhabited region and triggers other layers of secondary threats. These threats range from environmental contamination and its consequences to population displacement and depletion of critical infrastructure, such as healthcare and public security systems. Complex political, economic, and social interactions are also at play, including disaster preparedness. Responding to disasters is the most challenging activity of a society, as it mobilizes all of its resources. In a previous study by our group, we explored the concept of convergence methodology, also known as hybrid simulation methodology. This methodology involves comparing various mathematical or computational models working together to achieve a common goal [22].

4. CONCLUSION

The findings from the study provide valuable insights into the efficacy of complementary mathematical models in analyzing a radiological release scenario. Both analytical and numerical simulations yielded consistent results regarding TEDE estimation for a given location and local atmospheric stability conditions. Integrating various simulation models can substantially improve the ability to evaluate the situation and its consequences based on these outcomes. These results may have practical implications when the TEDE estimations are utilized as input in the equations for predicting radioepidemiological risks, enabling enhanced coordination and strategy development to address the crisis and optimize resource utilization.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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