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*Research article*

# Short-term urban resilience estimation after a hypothetical nuclear event

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**Abstract:** In the event of a hypothetical tactical nuclear device being detonated in a densely populated urban area, the first responders must be well-prepared to make immediate decisions with limited information. To aid in this preparation, a computer simulation using the HotSpot Health Physics code was conducted to model the detonation of a tactical nuclear device in an international airport and its surroundings, considering different yields ranging from 1 to 10 kilotons. The simulation was conservative and applied to a time window of 4 days in the initial phase of the response to the event. The simulation findings allow for assessing the immediate effects of the electromagnetic pulse (EMP) and the radioactive contamination plumes on an inhabited area. This assessment includes data on the size of impacted zones, compromise of critical local infrastructure, radiological risk to potentially affected populations, and estimation of urban resilience and its temporal dynamics. This information helps raise levels of protection and optimize available resources.

**Keywords:** urban resilience; computational simulation; nuclear device; consequence

## 1. Introduction

Studies dedicated to supporting decision-making in the context of environmental radioactive release events, whether this release is deliberate or accidental, have been gaining strength due to the engagement of large international agencies [1,2]. In general, methodologies for dealing with mass events of radiological or nuclear origin take as their center of interest the exclusion zones, identification, radiological dosimetry, and subsequent waste packaging in later stages of the process [3–7]. In recent decades, computer simulation, consequences modeling, and decision-making support based on urban resilience have accelerated [6,7]. This growth is driven perhaps by technological motivations and the influence of developing more powerful and accessible computational systems.

In the study context, resilience can be defined as the ability to withstand disruptive events while maintaining the power of critical structures to function at the highest possible level. Estimating the resilience of an affected urban area can be a highly valuable factor in determining a coping strategy. However, methods to quantitatively estimate urban resilience in this specific case are not area are the robustness and purpose of the local critical infrastructure [6]. The approach proposed in this study applies analytical and computational simulation to evaluate the ability to withstand a disruptive event. It generates a nuclear event in an urban zone. The evaluation of the probable impact on local critical infrastructure and the resilience of urban areas is achieved by adapting the 4π+ model for our group. This model enables us to assess the ability of individuals, communities, institutions, businesses, and systems within a city to endure, adjust, and prosper in response to various ongoing stresses and sudden shocks [8,9]. The developed model allows for determining and equating critical infrastructure vulnerabilities most relevant to the location. It considers physical dimensions related to the infrastructure and its development over time.

The hypothetical scenario simulated is limited by the detonation of a tactical nuclear device in an urban zone. The consequences for the population and critical infrastructure are conservatively included in the resilience estimation model in the event's first 4 days (≈100 h). The option for this timeframe in evaluating an event is because it represents a time when the risks associated with radiation exposure are higher. The actions taken during this phase may significantly impact the health and safety of the potentially affected population.

Applying the 4π+ model adaptation leads to information that may support immediate decision-making. This may imply better use of resources, damage mitigation, and zoning of impacted areas. The main argument of the work lies in the creative combination of concepts and variables to arrive at information that, if properly articulated, may produce an understandable picture of the actual situation.

Looking ahead to the future, our research group is developing an approach that can be applied to other fields of study. For instance, it can be utilized in food production to gauge the resilience of production chains in the face of climate change effects. Similarly, the same methodology can be employed in Forest Engineering to model disruptive events and estimate a specific area's environmental resilience. This can complement the process of simulating and predicting forest fires in real-time, as has been done by Cheng and colleagues [10]. In hydrology, efforts are being made to increase predictive capacity, which can help reduce environmental damage. The short-range flow forecast can be significantly improved by considering error covariances and data assimilation, and effective quantification of a posteriori errors on the estimates can be achieved [11].

## 2. Context and basics

Activating a tactical nuclear device with power ranging from 1 kT ≤ yield ≤ 10 kT (kiloton) in an urban zone is considered to take place within the active area of an international airport close to the main runway. Threats are supposed to emerge in two main aspects: (a) the effects of radioactive contamination plumes on urban zones and (b) the generation of an electromagnetic pulse (EMP). The two processes overlap, implying additional difficulties in the decision-making process in an attempt to mitigate effects on the population and critical local infrastructure.

The radioactive material that produces the equivalent of an environmental dose on the population can be presented externally and internally. The Total Effective Dose Equivalent (TEDE) can be defined as the sum of the external and internal effective dose equivalents. Four main routes of contamination can be considered: (a) inhalation, (b) ingestion, (c) incorporation by injection, and (d) absorption through the skin and mucous membranes. Theoretically, TEDE is considered a complete expression of the combined dose by measurable or estimable delivery routes. Determining isodose curves over the terrain is critical to define exclusion zones and risk levels in case a radioepidemiological model is applied.

An EMP occurs primarily by ionizing the atmosphere around the blast zone, producing electric fields in all directions. At ground level, the EMP is expected to propagate radially and symmetrically. However, for purposes of mathematical prediction, one can consider a vector with the preferred direction for the voltage and current pulse of electrons on the ground surface. These EMP depend on the explosion's power and location [12]. They can produce overloads on electrical systems, which will likely be neutralized. It is possible to create secondary EMPs originated by interacting gamma or X radiation with solid materials. This phenomenon is ordinarily referred to as system-generated EMP (SGEMP) [13], which is not considered in this study. The protection of electrical and electronic systems against the destructive effects of an EMP may include grounding, a procedure commonly used to protect against electrical storms (lightning). However, the nature of the current or voltage pulses generated by a nuclear explosion differs from an electrical storm in intensity, excluding using the same infrastructure protection model.

Crucial information for assessing the level of affectation of local critical infrastructure is the scope and intensity of the EMP. In a conservative approach, the study considers that the intensity of the EMP is sufficient to deactivate all sensitive components within the zone of effect. However, the mechanical, radiological, or electromagnetic range of the detonation of a tactical nuclear surface device is variable and depends on its power. In this study, values from 1 to 10 kT were tested, causing variations of 2 to 4 km for the reach of the EMP.

An essential problem that may arise when assessing the potential impacts on critical infrastructure is accurately estimating vulnerabilities. For this study, a central vulnerability is the deactivation of the energy supply, complemented by the destruction of equipment dependent on such electrical energy. Probable developments in services such as communications and healthcare are also expected. However, not all equipment within the EMP's circle of effects will fail or be destroyed, failure being more likely the closer to the trigger point of the main event. Equipment with components under solid-state technology or more sophisticated systems can often be more prone to failure than rudimentary devices such as valves. Thus, the least affected equipment by the EMP is electromechanical devices, including electric motors, heaters, and others. Because they have smaller antennas, cell phones are unlikely to be impacted by an EMP if disconnected from power lines during the pulse. However, even with expected functioning, they will not be of interest or help if the communication system goes down. The effects of an EMP are instantaneous and co-occur with the passage of the pulse. Damage caused to equipment within the range of the EMP will occur in this short interval of time but with lasting consequences. Electronic equipment disconnected from the electrical network in the area impacted by the pulse, which does not depend on other equipment for its operation, may function normally.

This study was developed by applying the HotSpot Health Physics version 3.1.2 code. This computational tool can estimate the emissions from activating a hypothetical surface nuclear device (fission). The simulations were performed using the HotSpot Health Physics version 3.1.2 code, produced by the Lawrence Livermore National Laboratory (USA). HotSpot is software capable of generating contamination scenarios based on minimal data input and with a user-friendly logic and video interface. It is a free code that can be used from a simple laptop with ordinary configuration for civil use. The applied theoretical basis is based on the fundamental work of Glasstone [12] on the effects of triggering nuclear weapons. The atmospheric release of radioactive materials and distribution of radiation doses are usually described based on studies on local atmospheric stability conditions, such as the study conducted by Pasquil [14]. Because of the energy levels delivered when activating the nuclear device, the calculations of ground-level radiation doses have a negligible relationship with local atmospheric stability and, therefore, are not addressed here.

Another critical aspect to be considered is the possibility of attenuation offered by urban shielding for immediate gamma radiation and precipitation delivered by physical structures (houses, apartments, soil, vehicles, etc.). Systems considered in the study are taken as isolated, so in a conservative approach, possible effects originated by adjacent structures were neglected. Considering radiological, radiation dose-related (TEDE), and non-radiological (EMP) consequences, the process was conservative. This approach overestimates damage and risk, which is interesting for an initial assessment. Over time, information takes on a more realistic outline and naturally produces an environment closer to logistical needs and available resources. Supporting decision-making without new crises or developments tends to become more adequate over time. This support primarily aims to assess the impacts on critical infrastructure. It seeks to optimize available resources to provide risk reduction, raise levels of protection for the affected population, and mitigate immediate harmful effects such as acute radiation syndrome (ARS) [15]. Atmospheric space and the ground have different conductivities, and an explosion at the boundary of the two environments causes additional asymmetries to the EMP phenomenon. The variation with distance of the peak radiated electric field along the ground surface is given by the equation (1) [12],

$$E = \frac{R_0}{R} E_0 \quad (1)$$

where $E_0$ in volts [V] is the peak radiated field at the radius $R_0$ [km] of the deposition region and $E$ in volts [V] is the peak field at the surface distance R, [km] from the triggering site.

The TEDE values calculated by HotSpot were applied as input data for radiation dose in solving the relative risk equation (RR) for solid cancers in general. This equation is based on the Japanese Radiation Effects Research Foundation (RERF) model [16] and is presented in its complete form in equation (2). The radiation-induced cancer development model is defined for whole-body radiation doses up to 4 Sv (sievert). This is the average lethal dose that 50% of the exposed population (humans) is expected to take in the following 30 days without any medical assistance [16]. There is no particular reason for choosing solid cancer as an example.

$$RR = r_0(a,s)[1 + \alpha_s D exp(\beta(e - 25))] \quad (2)$$

where $r_0(a, s)$ is the basic incidence rate of morbidity in the potentially affected population in the absence of radiation taken as the unity in this study, $\alpha_S$ is the age-specific linear excess relative risk per Gy considered as 0.45 ($Gy^{-1}$) and 0.77 ($Gy^{-1}$) for male and female, respectively. D is the radiation dose, TEDE, (Gy), *e* is the age (years), and β is the coefficient determining the modifying effect of age, both at the exposure, and considered as −0.026 ($y^{-1}$) for both sexes.

It should be noted that there are different radiation dose coefficients for the general public and nuclear personnel in cases of ingestion or inhalation. However, in the event of a release of radioactive material from a nuclear tactical device, both groups may receive comparable doses. Radiation protection standards for both groups consider the general public's conservative expectations, as personnel are at a higher risk of contamination and exposure. Therefore, higher levels of exposure can be expected for the general public within the affected region. It is worth highlighting that the equations used in radioepidemiology are derived from follow-up studies with survivors of the atomic bombings [16].

HotSpot provides data that allows one to estimate the area of each plume in the zone of interest. From a conservative perspective, these areas may, to some extent, represent a weighting factor to estimate the size of potentially affected populations. This estimate is conservatively provided from the simple product of the area of interest and the local population density. Based on previous results from our research group [9], Equation (3) facilitates a general assessment of resilience ($R_{es}$) by scoring it on a simple arbitrary scale, the level of impairment of the structures can be assessed.. The weights (k-terms) represent a fine adjustment for each variable. The k-terms are a kind of adjustment designed by decision makers and technical staff to represent the expected impact of compromising a given infrastructure. It is important to note that not all infrastructures are considered equal in terms of consequences, and their weights may change throughout the decision-making process. However, this condition is being studied within the scope of the $4\pi^+$ model and is currently based only on the empirical experience of decision makers.

Specific values of the k-terms were all kept as unity (k = 1). This is because in the timescale used (4 days) it would be unlikely to have access to enough detailed information to generate fine adjustments to the scenario. Fine adjustments are not considered in each plot; only the variables' absolute (gross) values are considered. Note that the variables of interest appear in the denominator of equation (3) parcels. This is because the event is being evaluated, looking for a figure of limitations, and thus, the higher the damage to a given infrastructure, the lower the level of resilience of the urban area of interest. Equation 3 comprises of the TEDE variable in its 2nd and 3rd terms, presented alone and associated with the local demographic density, respectively. While these terms may seem identical, the correction of the TEDE variable by φ(x) aims to offer more detailed and flexible information to update the total resilience value (Res) as the evacuation process progresses over time. To simplify and make resilience dimensionless ($R_{es}$), the constants $k_n$ were introduced in the same dimension as the corresponding variables. This means that each component of the $R_{es}$ indicator is dimensionless, resulting in a dimensionless output.

The dimensionless of $R_{es}$ refers to the units applied to the k-terms. Each portion of equation 3 is adjusted by a factor with units inverted to the variables to be evaluated. This factor is specific to each portion of the equation and allows the plots to become dimensionless. Normalization occurs by applying proportionality, where each installment contributes a specific fraction on a scale ranging from 0 to 10. However, normalization may be different at the discretion of the decision-makers in each scenario, just like the k-terms and the number of installments in Equation 3. To summarize, $R_{es}$ represents a scale value that refers to decision-makers chosen variables and critical infrastructure. Its representation on a scale can function both as a provider of situational awareness and as an indicator of the evolution of the state of things throughout mitigating actions. Although $R_{es}$ may become more complex with increased variables, it remains important in simplifying information for the population and local government.

$$R_{es} = \left[\frac{k_1}{yield}\right] + \left[\frac{k_2}{(TEDE)}\right] + \left[\frac{k_3}{(TEDE)\varphi(x)}\right] + \left[\frac{k_4}{\delta_{sex,age,TEDE}}\right] + \left[\frac{k_5}{AIS}\right] \quad (3)$$

where $k_n$, the adjustment factor ($k_n$ , with n = 1, 2, 3…) for this study, represents the balance for each location or affected zone, yield [kT], TEDE [Sv], φ(x) [inhab./km$^2$] is the maximum population density at a specific distance (x) from the device triggering location (conservative), Affected Infrastructure Selection (AIS) [dimensionless] is the selection of the affected critical infrastructure which represents the choice of decision makers about the critical infrastructure that should be considered in the model, and $\delta_{sex,age,TEDE}$ is the relative risk (RR) [Sv/Gy] for solid cancer estimate.

## 3. Materials

The calculations are conservative and consider Gaussian models for the atmospheric distribution of contamination plumes. Although they have limitations and errors are accentuated for distances greater than 10 km [17], they are fast and, therefore, suitable for evaluations in the event's initial phase. The study was designed to assess the situation within a 4-day time window. Probably little reliable information should be available at this time, and a conservative approach is adequate [8,9].

The explosion was simulated, and two threat fronts can be highlighted: a radial one that includes shock wave effects coupled to the EMP and another one referring to radioactive contamination plumes. These plumes were labeled according to isodose values of interest for the study: (a) 700 mSv represents a threshold for the appearance of deterministic effects of radiation and the onset of induction of acute radiation syndrome (ARS) [15]; (b) 100 mSv is considered a limit regarding voluntarism in attending and responding to the event and also a limit between high and low radiation doses [18], and (c) 50 mSv is a limit considered as an indicator for local evacuation actions [18]. The user chooses these values, and the simulation results are computed by HotSpot and selected by the user according to each objective. On this methodological basis, the geostatistical program Quantum GIS (QGIS) was used to visualize and evaluate geospatial data to estimate the potential impacts of activating the device for different layers of interest (population and critical infrastructure). To help assess the impact of the yield of the nuclear device on the TEDE, an additional calculation of the standard deviation (SD) for each urban shielding is introduced. Figure 1 presents a summarized situational diagram of the scenario.

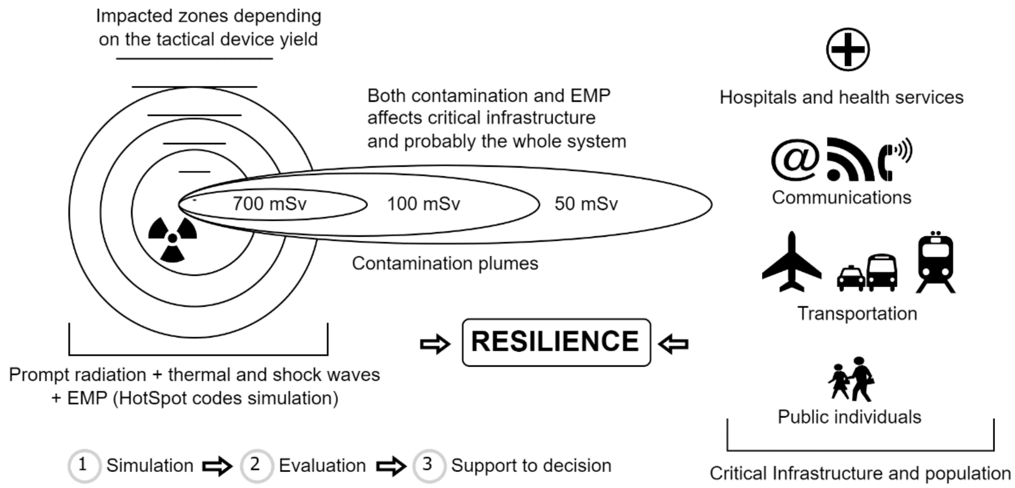


**Figure 1.** Situational scenario scheme.

## 4. Results and discussion

Figure 2 presents a clipping of the urban zone impacted by the detonation of the tactical nuclear device. The circles indicate different radii of the EMP projected onto the ground, the innermost being (3 km) for devices with up to 2 kT yield. The outer circle (4 km) refers to the range 2 kT < yield ≤ 10 kT. The impacted zone is an international airport (generic) and its inhabited neighborhood. The hypothetical event develops with effects on the population and critical local infrastructure indicated in the caption, which is usually robust due to the commercial and logistical activity developed around the airport.

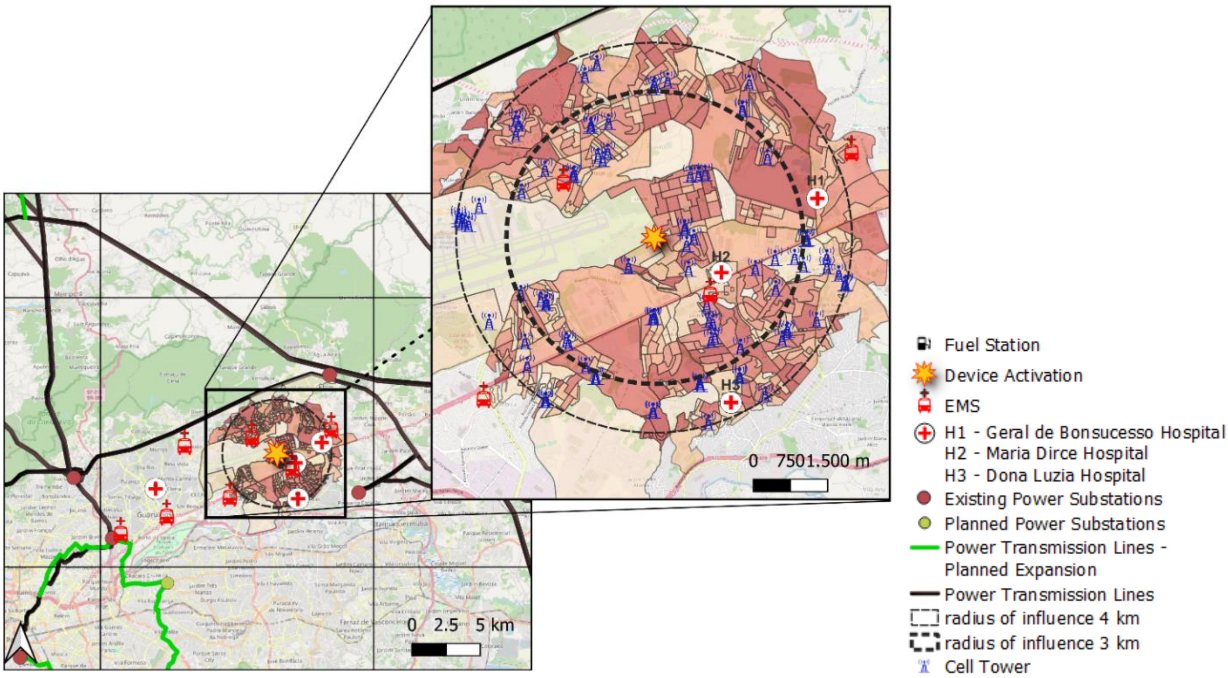


**Figure 2.** EMP zone of influence for the International Airport and urban vicinity's location.

Based on the input parameters used, the simulation indicates that the tactical nuclear device's radius of impact extends up to 4 km from the point of detonation. The EMP lines show two shutdown conditions with 3 and 4 km radii. This condition implies a possible compromise of the total (for yields above 2 kT) or approximately 30% of the hospital network if the power is less than 2 kT inclusive. Half of the fuel stations are expected to be compromised within a 4 km radius, no matter how powerful the device is (up to 10 kT). Without considering actions to respond to possible impacts of aircraft on the ground, since this deployment will depend on the density of air traffic at the time, there is a need for evacuation in areas contaminated by radioactive elements. These zones of radioactive contamination in the soil (isodoses) do not coincide with those represented for the EMP. They are partially contained in the concentric circles of electromagnetic disabling. The unavailability of fuel stations forces decision-makers to recalculate internal routes to contaminated areas. The device's power is related to the exclusion of peripheral fuel stations; however, it is unlikely that this information will be obtained promptly, leading to a conservative approach to managing the autonomy of transport. Using drones may be an interesting model for viewing the reach of the EMP and adjusting the available resources.

Although there is limited information on the direct consequences of an EMP on urban areas, it is likely that for yields above 2 kT, there will be a total compromise of the local electricity network within the radius considered. Some possible initial developments in the impacted region can be roughly predicted as follows:

a) There will be a total unavailability of electricity supply, interrupting traffic signs in places where traffic is still possible.

b) The EMP will disrupt communications and silence cell phones due to the definitive deactivation of signal transmission antennas, impacting the effectiveness of distributing security information and civil guidance.

c) Vehicles, especially those whose operating principle is based on electronic control units, will be abruptly deactivated, which could cause serious accidents.

d) Although an EMP can permanently deactivate any vehicle, a recent study shows that it is possible to overcome the EMP event with the continued operation of fuel transport trucks [17].

e) The EMP event occurs in a three-dimensional manner, which implies the deactivation of aircraft within its range.

f) As electrical systems turned off during the EMP event are preserved, subsequent assessment and reconnaissance actions can be conducted with the support of drones carrying cameras and radiation detectors [19].

Although the region affected by the activation of a 10 kT surface tactical nuclear device is limited to a maximum radius of 4 km, radioactive contamination zones can form sub-regions of varying intensity and shape. These subzones are mainly caused by contaminated soil and fallout effects, which follow the atmospheric dispersion of contaminants. A Gaussian model is used in this study to predict these contamination zones. Isodose curves are used to delimit these subzones, which cover a specific area and vary in size and direction based on local atmospheric stability conditions. Figure 3 presents the zoning for TEDE values in $km^2$, which can be used to estimate the number of individuals in the affected region by multiplying the area of the affected zone and the local demographic density. This approach is useful in the initial phase of confronting the crisis. However, it is a conservative approximation where the area of the affected zone is considered constant, and the population density is uniform. On the other hand, the EMP event, which remains independent and has a short duration compared to the fallout effect resulting from the explosion, does not interact with local atmospheric variables. Therefore, the EMP event is represented in kilometers in Figure 3 (right axis), as only the range of the EMP is of interest and presents such symmetry that the entire reaction is affected similarly in the hemisphere. Figure 3 presents the areas (km²) under the radioactive contamination plumes, representing the isodoses for TEDE of 700, 100, and 50 mSv (left axis). At the same time, it indicates the expected ranges for the EMP as a function of the powers (yield) of the tactical nuclear explosions (right axis).

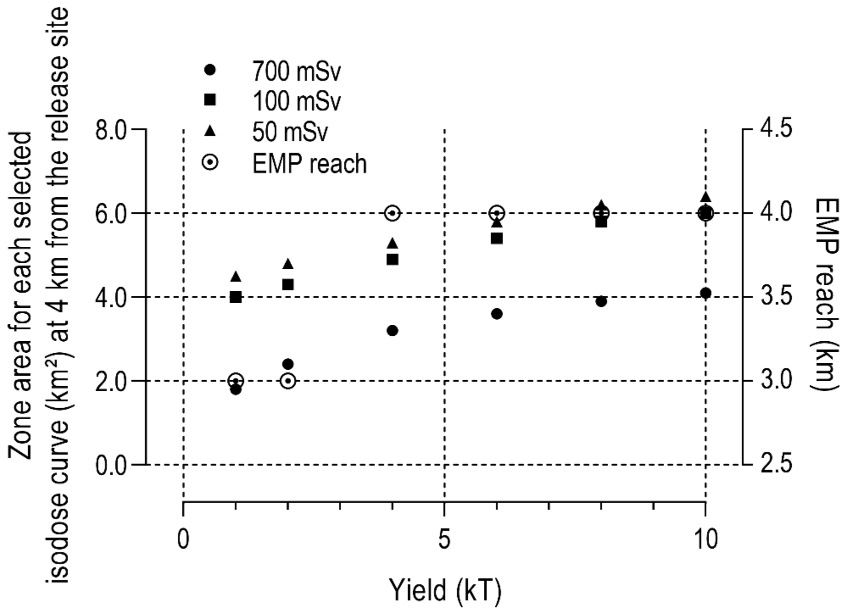


**Figure 3.** Zones areas for the selected radiation isodoses (700 mSv, 100 mSv, and 50 mSv) and EMP reach depending on each tactical nuclear device's yield. The right axis is independent and only considered within the range of EMP.

As expected, the areas of the impacted zones grow proportionally to the potency of the device for any isodose values (TEDE), suggesting the increasing inclusion of impairments via EMP. The findings also recommend an increased limitation trend, reaching 6 km² in the interval 1 kT ≤ yield ≤ 10 kT. An implication of this phenomenon on the resilience of the affected urban area is the possible negative effect on the circulation of vehicles and the probable interruption of communications. These impacts range from the collapse of traffic signs, passing through non-compliance with isolated cases, and reaching the impediment of evacuation actions in large areas at the outermost limits of the isodoses (50 mSv). The radius of the circular zone affected by EMP varies from approximately 3 km (1 kT ≤ yield ≤ 2 kT) to 4 km for powers in the range 2 kT < yield ≤ 10 kT, changing the dimensions of the exclusion zones. These zones should be avoided, have limited access to, or have been evacuated, demanding specific coping strategies. It is possible to estimate some immediate impacts: (a) Due to the simulated power range (1 kT ≤ yield ≤ 10 kT), variable blocking of escape routes is expected, producing a bias for the decision process until a reliable radiometric survey is obtained; (b) each isodose (700 mSv, 100 mSv, and 50 mSv) produces a specific responsive behavior whose needs depend on the availability of the local critical infrastructure that may also be hastily compromised, and (c) EMP range radius depends on tactical device power and varies in range 3 km ≤ $EMP_{reach}$ ≤ 4 km. Although there may be doses of environmental radiation beyond the maximum reach of the EMP, the collapse of electrical systems in the affected area may represent a limiting factor for immediate care related to item (b).

For a conservative assessment of immediate risks, including composite threats (EMP effects and radiation dose), an event response protocol may find support in simple simulated exercises (table-top) based on this study. As in the present context, such practices should consider the different powers the tactical nuclear device delivers. Simulation results may help identify vulnerabilities that negatively impact local urban resilience. For this work, local urban resilience is limited to the impact on access roads, radiation doses (TEDE) resulting in radiological risks, and dependence on local electricity networks.

In the specific context that involves public exposure to radiation of the local energy system, the vulnerabilities due to the supply of energy to hospitals deserve to be highlighted: the interdiction of public roads, the disarming of electrical distribution networks, disruption of the communications system, and reduced public safety. Following an EMP, one of the primary communication challenges will be maintaining the functionality of cell phone towers. Concerning cell phones, transmission towers within range may be rendered inactive without a redundant system separate from the electrical grid and turned off during an EMP event [12]. Although cell phones and handheld radios have relatively small antennas and may not be affected if they are not connected to power during an EMP, they still rely on intact communication infrastructure. Even if the transmission towers withstand the EMP, connected cell phones, even those not connected to the electrical grid, may be deactivated, leaving devices turned off and disconnected from the grid. Consequently, investigating the impact on cellular network signal transmission towers may be worthwhile, particularly restoring this communication system facet. This is essential for effectively communicating with survivors and providing them with critical information on protecting themselves and responding appropriately.

Figure 4a shows the shielding offered by urban structures to radiation and TEDE for each power condition of the devices in the first 4 days at 4 km from the event, which is the maximum reach of the EMP for the powers used. Figure 4b presents the standard deviation (SD) values for each urban shielding, highlighting the impact of each urban shielding type on the expected TEDE as a consequence of the devices' yield. The standard deviation (SD) was used to assess the dispersion of TEDE (Total Effective Dose Equivalent) values for each urban shielding considering the variation of the yield produced in the event. This may help to estimate how sensitive, or insensitive, a particular shielding type is to yield variations in relation to the expected TEDE. For instance, through this method, it can be determined that the basement is less sensitive to yield variation than a frame house in terms of the expected TEDE for an individual in that condition. The influence of the device's power is shown in Figure 4a for each type of shielding offered by urban shielding. The radiation dose reduction effects on the population are maximized for 1 m underground, concrete 12" (pol.) walls, and multistory buildings' upper-floors.

The estimation of the relative risk (RR) for solid cancer development allows different evaluations because it generated results in different contexts: (a) ages between 20 and 70 years, (b) both sexes, (c) 3 isodose zones (700, 100 and 50 mSv) implying the variation of actions for each TEDE level, (d) device's power ranging from 1 to 10 kT and (e) three-time points (1 h, 1 day and 4 days after the event). For example, Figure 5 presents the RR ratio in a specific comparison between no-shielding and shielded (frame house) condition. The ages of individuals in the public were included in the range $20 \leq \text{age} \leq 70$ years, as well as all yields and times at a distance of 4 km from the trigger point. To evaluate the impact of age and sex variables for each power of the device, the standard deviation (SD) value was added for each distribution of ages in each yield. The SD is a way to assess the influence of the age variable on the expected biological effects, the relative risk (RR) of solid cancer development, for each artifact power level and TEDE at the 4 km radius location. SD values labels for each power are added in the figure for each frame house/no shielding ratio value for both sexes. Figures 5a and 5b refer to males and females, respectively.

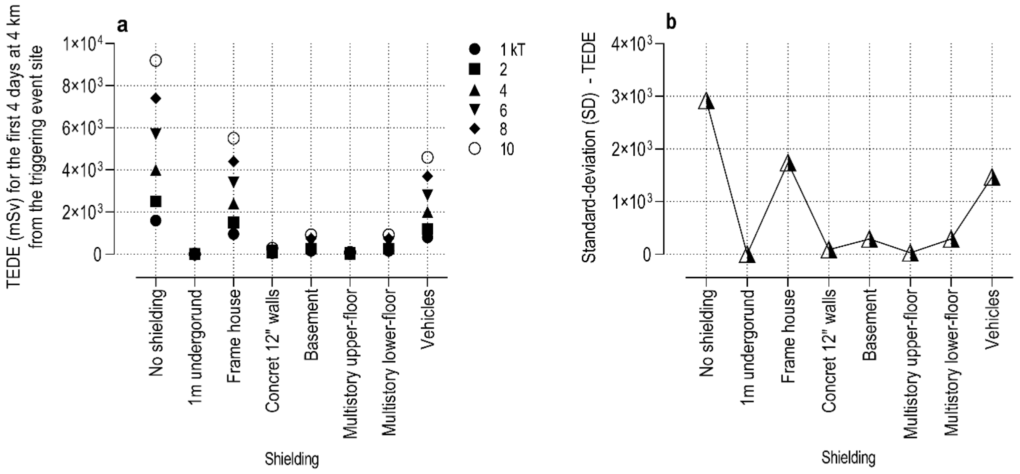


**Figure 4.** a: Radiation shielding, TEDE, and b: SD for each yield and urban shielding in the first 4 days at 4 km from the triggering event.

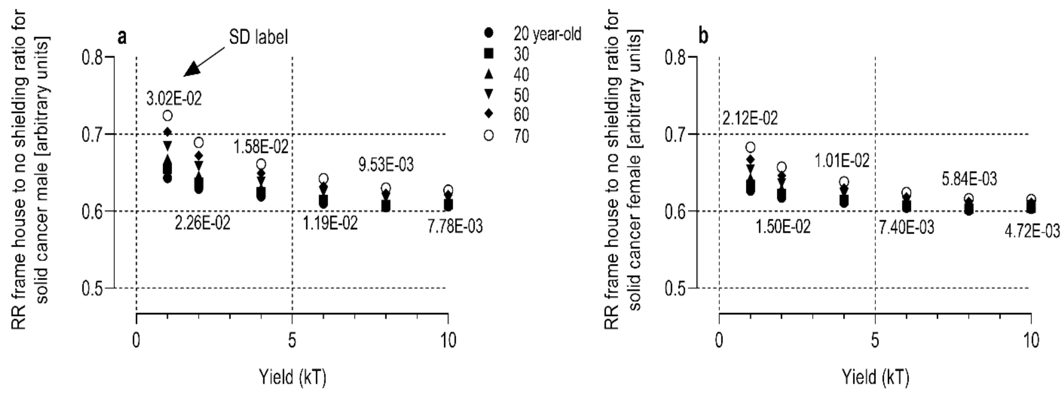


**Figure 5.** Relative risk (RR) ratio for a specific case of comparison between sheltered (frame house) and unprotected (no shielding option), ages 20 to 70 years. All yields (1 to 10 kT) at a distance of 4 km (conservative) from the triggering point, four days since the initial event.

From the results presented in Figure 5a, b, the more substantial influence of the individual's age on the risk for each potency is verified. The standard deviation values for each data series indicate that the influence of age may be comparatively increased for males. This analysis merges the RR values computed by the epidemiological model with the impact of different types of urban shielding on the TEDE for each device output. In comparing males and females for the same urban structures, the combined outcome shows that the epidemiological expectation holds true, with males being at a disadvantage depending on age. This information may be of value for prioritizing evacuation concerning the variables of sex and age of individuals if there are operational conditions for this. The model for RR calculations was solid cancer development [16]. This model implies long post-radiation exposure times, and its adequacy can be adjusted depending on the simulation objectives. Other models prepared by the same committees (BEIR V, VII, and RERF) may be used, and their combination can generate a more complete epidemiological picture of the situation. Despite all the limitations, associating data on relative risk (RR) by age group and sex with data on radiological exposure avoided by urban shielding remains a reasonable option.

Figure 6 presents results regarding the resilience estimated by eq. 2 for the higher-risk case represented by the *no-shielding* scenario (the most conservative). The times were 1h, 1 day, and 4 days for all device powers. Resilience estimation was performed by taking the average RR in the no-shielding condition for males and females. This exposure is a benchmark for the study because it represents the highest possible TEDE and allows comparisons. The only variable used to estimate the changes in Res (resilience) over time was TEDE (Total Effective Dose Equivalent). However, other factors could become more important over time. For example, local climatic conditions can vary, leading to changes in the TEDE profile. Similarly, re-establishing communication networks, even in a rudimentary form, can affect the ability to assess damage and influence evacuation protocols. There may also be other variables and local characteristics that can affect the evolution of the resilience status (Res) and its estimation.

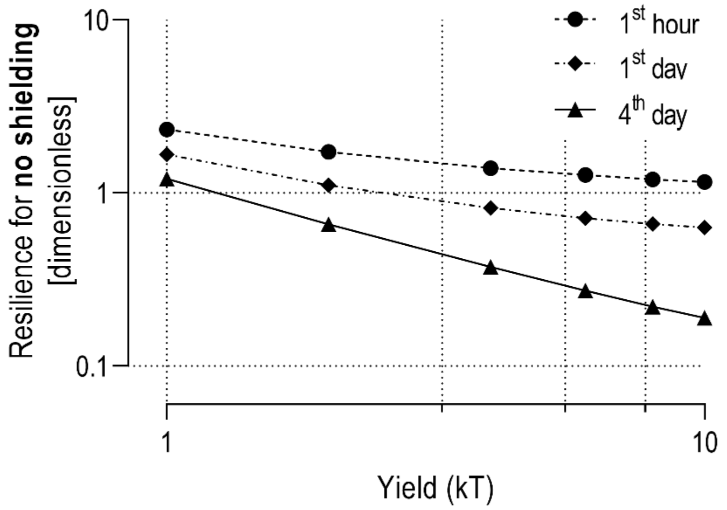


**Figure 6.** Estimating resilience dynamics for the no-shielding case 4 days since the nuclear event.

As a result of evacuation actions in the area with the highest TEDE expectation (700 mSv), it was considered that the local demographic density is reduced by 50% for each time taken (1h, 1 day, 4 days). On the contrary, the Affected Infrastructure Selection (AIS) utilization factor increases, and the availability of resources decreases at the same rate (50%) for each time taken. This dynamic is hypothetical serving only as a model for the early evaluation. Notably, the coping strategy should change over time, possibly influenced by factors such as the need to allocate additional resources, workforce exhaustion, and improvement of available information. Although such an assessment is outside the scope of the study, a negative variation in the rate of local urban resilience over time may be perceived. Although elementary, this observation may be of value to support decision-makers regarding the urgency of allocating resources at the highest level at the beginning of actions.

The results of this study indicate the sending of Unmanned Aerial Vehicles (UAVs), such as drones, to inform initial actions. However, this decision would face difficulties imposed by the lack of electricity, representing obstacles to any responsive initiative. As it is a place of maximum security for contamination and radiological exposure, the effort must be focused on informing the individuals in this condition until evacuation actions can be carried out. The situation that causes the most significant risk is that of individuals on the streets without protection of any kind. These individuals' amounts depend on the time of day and week and may represent amounts above the action capacity. However, considering that they are in an uncovered location, drones may be indicated for guidance even if there is no possibility of immediate electronic communication. Drones can drop previously produced pamphlets under the suggestion of table-top exercises, with prompt and easy-to-understand guidelines. Assessing the protective capacity offered by urban shielding may guide prioritizing zones to be attended to. This prioritization may be driven by access to local roads, dose levels (TEDE), and local population density.

Computer simulations and mathematical modeling are safe methods for evaluating the impact of a nuclear event on critical infrastructure and its potentially affected populations. However, it is essential to note that each event and phase has unique characteristics that must be considered when selecting the appropriate model and approach. It is essential to have flexibility, knowledge of available tools, and familiarity with approaches that maximize positive outcomes for at-risk populations. These efforts can be divided into two main aspects: prospective and real-time assessments. Therefore, based on estimated data, this conservative study can be a valuable reference for prospective actions that prepare response forces beforehand while simultaneously identifying vulnerabilities in local systems and essential infrastructure.

## 5. Conclusions

The methodology applied using analytical, computational simulation, and mathematical modeling for assessing resilience is relatively easy. Also, it offers a user-friendly interface and records relevant results. Epidemiological models are valuable tools that can be used to categorize individuals at high risk of contracting a disease based on age and gender. The sensitivity of relative risk varies with these two variables, making it essential to consider them when developing risk stratification models. By utilizing epidemiological models, it is possible to understand better and predict disease outbreaks, helping to inform targeted interventions and improve public health outcomes. This characteristic of the study can facilitate decisions that include the need to prioritize care, given resource limitations, and the decision on prioritization always represents a significant obstacle to be overcome. since resilience degenerates in the first hours, we can focus additional studies that optimize logistics for dealing with these degenerating conditions.

## Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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**Conflict of interest**

The authors declare no conflict of interest.

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