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Computational Decision Support Systems Applied to Decision-Making Process in the Emergency Planning of the Angra dos Reis Nuclear Power Complex – Brazil

Sistemas Computacionais de Suporte à Decisão Aplicados ao Processo de Tomada de Decisão no Planejamento de Emergência do Complexo Nuclear de Angra dos Reis - Brasil

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Abstract

Industrial accidents pose risks to the entire environment located in the area of influence of the enterprises, especially when they are affected by the atmospheric dispersion of pollutants emitted, as in the case of a nuclear power plant, where the concern with the evacuation of the population is the main priority in critical situations , which reinforces the implementation of actions to support emergency planning and its management, whose support tools, among them the computational modeling that, based on atmospheric models and geographic information systems, are essential in the decision making process. Thus, based on the Angra dos Reis nuclear complex and the impacts that may affect its surroundings, studies using the integrated use of computational platforms served to evaluate the risks and consequences of a hypothetical accidental event, including the calculation of the thermo- source of nuclear fuel, meteorological characteristics, mechanisms of atmospheric dispersion of pollutants, as well as socio-environmental aspects of the region. Meteorological data (wind regime) characterize the wind field from the WRF model, which subsidized the dispersion of radionuclides calculated in the HYSPLIT, information associated with socioenvironmental data (landslides, population density, etc.), incorporated in a GIS database. The results demonstrate the importance of the integrated use of computational systems as tools that support decision-making, potentializing the application of solutions that contribute to support actions and guidelines of planning and governance in emergency situations.
Keywords: Decision support systems; Nuclear emergency management; Dispersion of radionuclides, WRF; HYSPLIT; GIS

Resumo

Acidentes industriais representam riscos para todo o ambiente situado na área de influência dos empreendimentos, especialmente quando são afetados pela dispersão atmosférica de poluentes emitidos, como no caso de uma usina nuclear, onde a preocupação com a evacuação da população é a principal prioridade em situações críticas, o que reforça a implementação de ações para apoiar o planejamento da emergência e sua gestão, cujas ferramentas de suporte, entre elas a modelagem computacional que, baseada em modelos atmosféricos e sistemas de informação geográfica, são essenciais no processo de tomada de decisão. Assim, tendo como cenário o complexo nuclear de Angra dos Reis e os impactos que podem afetar o seu entorno, estudos com o uso integrado de plataformas computacionais serviram para avaliar os riscos e as consequências de um evento acidental hipotético, incluindo o cálculo do termo-fonte do combustível nuclear, as características meteorológicas, os mecanismos de dispersão atmosférica dos poluentes, bem como os aspectos socioambientais da região. Dados meteorológicos (regime de ventos) caracterizaram o campo de vento a partir do modelo WRF, que subsidiou a dispersão de radionuclídeos calculadas no HYSPLIT, informações associadas aos dados socioambientais (deslizamentos, densidade populacional, etc), incorporadas numa base de dados SIG. Os resultados demonstram a importância do uso integrado de sistemas computacionais como ferramentas que apoiam a tomada de decisão, potencializando a aplicação de soluções que contribuam para subsidiar ações e diretrizes de planejamento e governança em situações de emergência.
Palavras-chave: Sistemas de suporte à decisão; Gestão de emergência nuclear; Dispersão de radionuclídeos; WRF; HYSPLIT; SIG

1 Introduction

The long period of prosperity of the worldwide economy after the war, according to Silva (2007), was characterized by the growth and development of several branches of the economic activity, especially the industries in general, from which the nuclear segment stands out. The quick development of the industries and their technologies was supported by the scientific knowledge, which, accumulated by the several areas that integrate it, was strongly fostered during WW2. Haguenauer (1986) assessed that, not only due to the need for products for military purposes and driven by a series of political and economic factors, such period demanded a volume of other products, such as medication, power, materials and fuel, which could not be supplied by natural raw materials.

In spite of the contribution that the industrial development made to improve society's quality of life, Souza-Júnior (2002) highlighted its costs, especially those of an environmental kind, which, with the degradation generated by such products, cause harm to modern society, which means that the industrial development has consequences inherent to the problems usually associated therewith, such as degradation of the environment, the appearance of occupational illnesses and workplace accidents. In this regard, there currently is an immediate need to associate the production of industrial activities to a series of measures that also prevent harm to the society.

Considering such perspective, Silva (2007) stressed the importance of analyzing the modern industrial development not only by the economic and technological increment that it provided, but also by the aspects that point to the increase of the potential of seriousness of the accidents, resulting from flaws in the operation of industrial, transportation, power and other systems, the causes of which, according to Freitas (1996), result from several factors, including technological and human failures and mainly management and organizational flaws that permeate the social relationships at the workplace and the mode of operation of technological systems.

Upon analyzing the occurrence of accidents in the industry in general and also in the nuclear segment, it is noted that the existence of an emergency response plan contributed to mitigate the magnitude of the damages, in that they affect mainly the population. Thus, by analyzing the consequences occurred, several countries were led to review their emergency response plans, in the technical and scientific departments, where new researches were carried out, in relation to nuclear safety, especially for the management of nuclear accidents with catastrophic consequences.

In the nuclear segment, especially due to the accidents that occurred in the 70s and 80s and, more recently, in Japan in 2011, the matter of safety has been questioned by society in general, mainly because of the frailty that such enterprises have demonstrated when the causes and main consequences resulting from accidents occurred are analyzed in depth.

Due to the complexity and specificity of each area where a nuclear central is located, the planning and emergency actions need technological components that incorporate more and more tools able to assist in the decision-making in emergency situations, integrating representative aspects of their areas of influence.

Regarding the vulnerability of the populations who live close to industrial enterprises, Freitas *et al.* (1995) stated that such problem is supported by the lack and frailty of legal restrictions and social control of the chemical risks in the developing countries, worsened by the greater social vulnerability of the exposed population, and the factors that contribute to such situation, as Quarantelli (2000) sees it, are:

- Growing urban concentration and consequent increase of the population density close to the risky areas;
- Several issues and daily needs faced by the greatest part of the population living in those areas;
- Low socio-economic standards, different family standards and lifestyles, as well as demographic distribution, which is predominantly composed by children and elderly citizens.

Such reasons are a part of the reality in Brazil which, especially due to the lack of urban and land planning, public policies and socio-environmental control policies, gives rise to a disordered occupation in the environs of industrial areas under risk, which renders the communities located close by vulnerable and exposed to the occurrence of accidents, in addition to problems caused by air pollution and/or other consequences from the industrial processes that caused some kind of impact.

Observing the risks caused by industrial enterprises, Silva (2007) analyzed the importance of assessing the vulnerability of the areas in the environs of industries, emphasizing the set of variables that must be appraised, considering the local environmental dynamics, from which the following stand out: population data, infrastructure survey, transportation system, socio-economic and environmental data and others. A set of such information allows an in-depth understanding of the area under the enterprise's influence and the characterization of such data constitutes an important element for the conduction of a much more accurate risk assessment, allowing a more efficient planning in relation to risk management and the emergency response actions.

The issues caused by catastrophic events, in the opinion of Gonçalves Júnior (2006), can lead to high levels of radioactivity in the environs of the plant, representing a threat to human life, society and local life. Thus, considering the scope of the impacts that a nuclear power plant can cause, especially due to the dispersion of radionuclides into the atmosphere, the meteorological aspects must be observed first, in order to serve as parameters to simulate the behavior of dispersion in the area of influence. In addition, in order to integrate such information and become aware of the scope of the impacts on the geographic space, it is necessary to represent the environmental dynamics with the set of data, which include aspects different from the local geographical, biological and physiographic reality of the site, with the purpose of assessing the vulnerability of such elements to the impacts generated.

This study aims to demonstrate the importance of using a system to support the decision-making process, through computer simulations, the results of atmospheric information, mechanisms of dispersion of radionuclides, together with the georeferenced environmental data from the region influence and its integrated analysis helps to support actions in emergency response planning after a hypothetical accidental release of radionuclides from the Angra dos Reis Nuclear Complex (CNAAA).

2 Study Area

The study area is located at the southern coast of the Rio de Janeiro state, and encompasses the area under the influence of the Angra dos Reis Nuclear Power Plant (Latitude 23°0'27.21" S; Longitude 44°27'31.43" W), bordering on the Emergency Planning Zones (EPZ), which encompass radio of up to 15km around the CNAAA. The population density of the environs, according to the 2010 Census (IBGE, 2012) was of 205, 45 inhab/km^2 in Angra dos Reis and 40,57 inhab/km^2 in the city of Paraty, which characterizes a complex geographic space due to the population dynamics that currently houses a total of 194,619 inhabitants (estimated data from the IBGE, 2017) in Angra dos Reis only.

The region is located between the Ilha Grande bay and the Serra do Mar mountain range, with Angra dos Reis, Mangaratiba and Paraty being the main cities (Figure 1). It is formed by peninsulas and inlets, mountains and rocky coasts. The Atlantic forest is the dominant vegetation, especially due to the relief, constituted by hills of high and average declivity, which dominate the landscape. The place where CNAAA is located is the back of a bay, surrounded by hills and high mountains, from the West (W) to the East (E), with the Ilha Grande bay to its Southwest (SW) / South (S) / Southeast (SE) side. The geomorphological characteristics show a strong and undulated relief, with escarpments, steep sides and high declivities.

The region has complex atmosphere circulation mechanisms, especially due to the characteristics of the relief and proximity to the ocean, which determine the winds at the region. The local meteorological scenario, characterized by the predominant wind directions, atmospheric intensities and stability, according to Silva (2013), are crucial to define scenarios based on specific models, mainly in relation to atmospheric pollutant dispersion, such as radionuclides, which contributes to the decision--making process in emergency situations, especially in the evacuation process and establishment of escape routes.

Based on observational data on the region, Oliveira Júnior (2008) described the main existing systems and the main predominant wind direction and intensity. Acting synoptic systems, such as the Passage of the Weather Front (Passagem do Sistema Frontal - PSF), occur mostly from May to September. High-Pressure Systems (Sistemas de Alta Pressão - SAP) are predominant in July, September and November. Re-assessment data have shown that most winds follow the WSW and SSW directions (1000 and 925 hPa), S and SW (850 hPa) and E and ESE (700 hPa). Oliveira Júnior (2008) appraised the wind scenario at the surface, from four weather stations located at the environs of the CNAAA. For the weather station called Tower A, the data from which were used at the 100m level, the study indicated the following results: the N direction prevails, followed by S and SW (Oliveira Júnior, 2008). Regarding the wind intensity, the average values for all periods were around 5 to 8 m/s. According to MRS (2006), comparatively the percentages of calm weather in the 4 towers vary from 15% to nearly 40%, ranging from 35 to 47% at tower A100. Oliveira Junior (2008) identified the existence of two predominant classes in the environs of the CNAAA: calm weather and winds with intensity of 1 - 3m.s^{-1}, with average speed of about 2m.s^{-1} and wind scenario with no significant seasonal variation. As a conclusion of the study, a low capacity for pollutant dispersion due to the predominance of stable classes and wind intensity lower than 3m.s^{-1} were indicated. Due to such characteristics, the adaptation of computer models of the

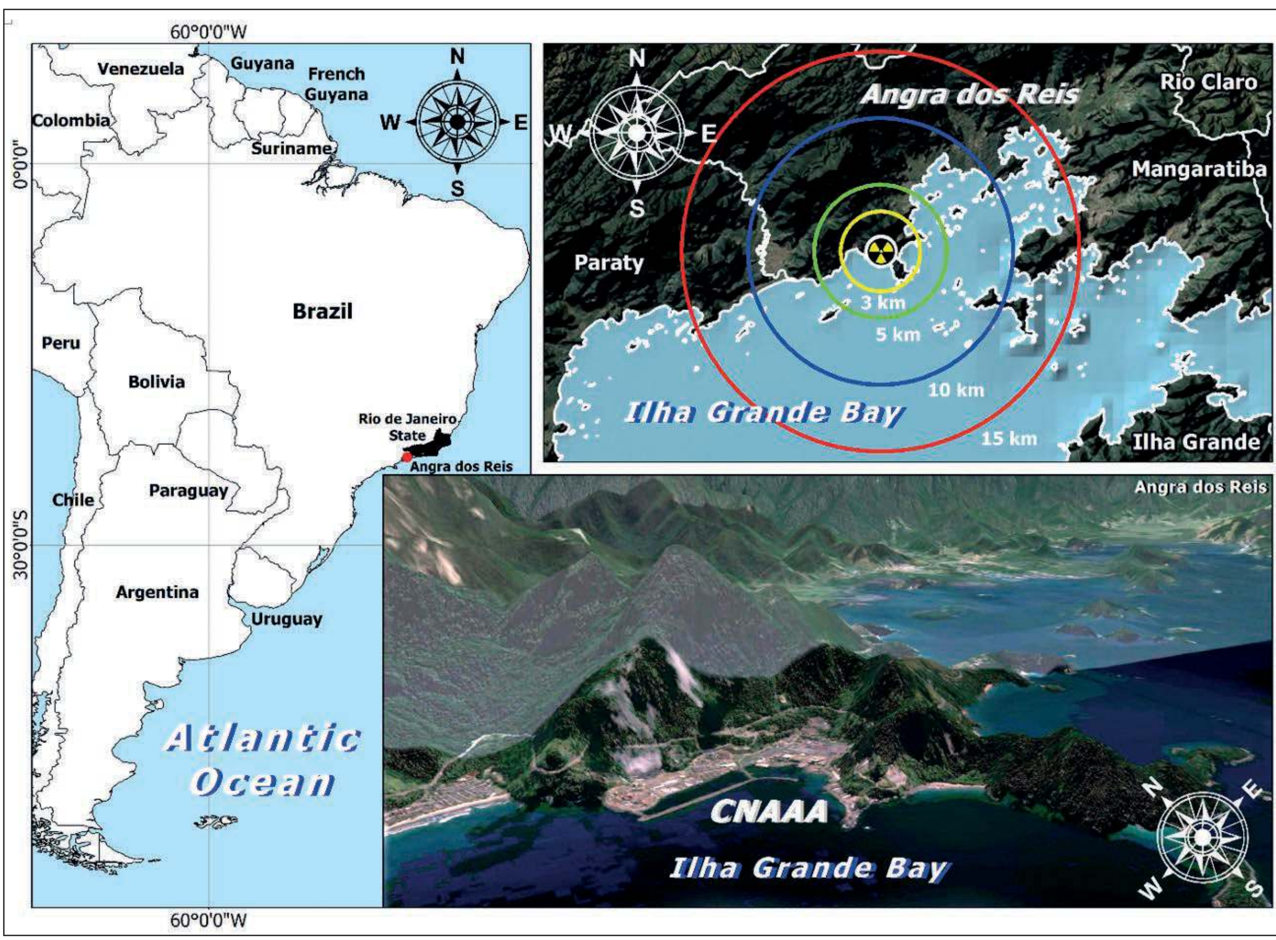

Figure 1 Location of the study area.

atmosphere that realistically show the influences of the micro-scale and mesoscale systems that occur in the region, to allow the subsidy of studies pertaining to pollutant dispersion, is a great challenge.

In relation to rainfall, based on a 25-year pluviometric series (1980-2004) and analyzing the pluviometric records of CNAAA's site, Soares (2006) made a diagnosis of the average climatologic rainfall in the region, identifying the months with greater pluviometry during the year: January, February, March and December.

In economic terms, the main activities are: industry (naval, nuclear and oil), commerce and tourism; responsible for the attraction of migrants from the metropolitan region and other areas of the state of Rio de Janeiro.

The interaction among the local geographical, biological and physiographical aspects confer complexities to the region, of which landslides, rainfall, population flow, use of soil and other important elements stand out, especially when associated to emergency situations and the planning of response actions to accidents at the CNAAA.

3 Material & Methods

The methodological procedures, as described in Silva *et al.* (2013), initially included the identification and acquisition of socio-environmental data on the region, so as to contribute to the analysis of possible environmental impacts and the proposal of scenarios occurred after accidents at the CNAAA.

A subsequent stage consisted of the incorporation of such data into a Geographic Information System (GIS), by means of platform ArcGIS 10.4, where the following items of information were integrated: population distribution, location of bodies of water, places of occurrence of landslides, main escape routes, fishing sites, location of the conservancy units, among others; the purpose of which was to subsidize the integrated analysis of the impacts by the emission of radionuclides on such environments. In addition, considering the seasonal and daily meteorological conditions of the region and the information pertaining to the main landslide areas for each time of the year, important analysis scenarios were identified.

Simulations were made with the air quality modeling system, composed by the WRF (Weather Research and Forecasting) meteorological mesoscale model and by the Lagrangian model of pollutant dispersion HYSPLIT (Draxler & Rolph, 2003), the results of which were inserted in the GIS database, where jointly with the other data collected they allowed the assessment of the impacts of the accidental emissions of radionuclides, subsidizing the decision-making process during emergency situations and the population evacuation process.

Based on the proposal of an idealized scenario, representing a nuclear accident at the CNAAA with the release of radionuclides, a mathematical-computational model was developed, with the aid of the symbolic mathematics platform Mathematica 8, for the determination of the source term. Such information, which consists of the calculation of the rate of emission and identification of the main radionuclides released, were used as entry data for the pollutant dispersion model HYSPLIT.

Interpretative analyses of the different correlations among the variables regarding the theme allowed the creation of an integrated system for the problem proposed, allowing the understanding of the local spatial and temporal dynamics, associated with the occurrence of accidents at the CNAAA, with the release of radionuclides, the planning of emergency response actions and the mitigation thereof. Figure 2 shows the structure of the computer simulation developed.

4 Results & Discussion

The main results of the research produced a set of elements that contribute for the scientific enrichment of information on the region and the knowledge of the aspects that integrate its geographic space, the relation thereof with the local reality and the importance of the integrated analysis of its complexities and information, especially with the purpose of local planning, considering situations connected to the emergency response process. Thus, the following products were developed:

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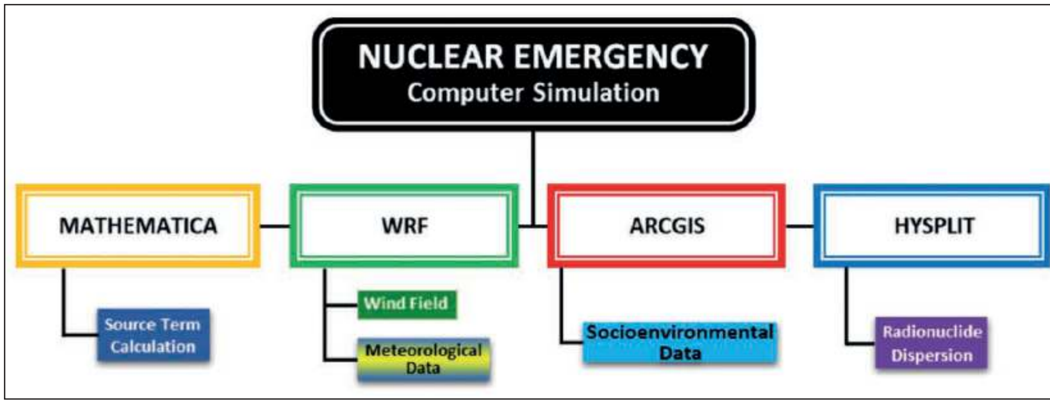

Figure 2 Structure of the computer simulation developed for the research.

- Calculation of the source term for the radionuclides I129 and I131;
- Socio-environmental data on the studied area;
- Meteogram of the wind field data observed from Tower A and occasional simulation results obtained with the WRF weather forecast model;
- Radionuclide concentration scenarios obtained with the HYSPLIT - I129 and I131 dispersion model.

4.1 Calculation of the Source Term

Upon analyzing the specific activities for the radionuclides assessed, the following were determined: short half-life and long half-life; the calculation of the emission rate (released activity) of the products of fission observed, considering the maximum activity at the reactor after one year and a total release of the stock in 24 hours for the radionuclides indicated. Thus, the emission rates were calculated for short half-life radionuclides (I131, Xe131 and Xe133) and long half-life radionuclides (H3, Kr85 and I129), one of each group having been used in the HYSPLIT simulations: I131 and I129. Table 1 summarizes the calculations made. The emission rates were turned into gram per hour and inserted into the model, where the process was simulated considering the dispersion in the first 15 hours, according to the result on the wind intensity and direction.

From the viewpoint of the risks that such values pose, we can state that for dose rates of the order of fraction of mSv/h, the risk due to inhalation is low. Of the order of mSv/h, the risk can be considered to be medium; fractions of rate of a dose of Sv/h can be considered a high risk and of the order of Sv/h very hazardous, which allows us to build the table below (table 2), which indicates the type of risk according to the concentration in g/m3, respectively for I131 and for I129.

Radionuclide	Low Risk	Medium Risk	High Risk	Very High Risk
	Concentration values in g/m^3			
I131	$\leq 10^{-11}$	$>10^{-11}$ and $\leq 10^{-10}$	$>10^{-10}$ and $\leq 10^{-9}$	$>10^{-9}$ and $\leq 10^{-8}$
I129	$\leq 10^{-3}$	$>10^{-3}$ and $\leq 10^{-2}$	$>10^{-2}$ and $\leq 10^{-1}$	$>10^{-1}$ and $\leq 10^{0}$

Table 2 Risk connected to the I131 and I129 radionuclide concentration band, when given in g/m3.

Radionuclide	Total quantity in the reactor (g)	Specific activity (Bq/g)	Emission rate in 24 hours (Bq/s)	Emission rate in 48 hours (Bq/s)	Emission rate in 24 hours (g/h)	Emission rate in 48 hours (g/h)	Dose Factor - Inhalation (Sv/Bq)	Dose Factor of the Program (mSv/h)/(g/m^3)
I131	202,3562116	4,59E+15	1,08E+13	5,38E+12	8,43E+00	4,22E+00	7,49E-09	4,13E+10
I129	3419,882292	6,55E+06	2,59E+05	1,30E+05	1,42E+02	7,12E+01	3,95E-08	3,10E+02

Table 1 Calculation of the radionuclides used.

One can note from the table above that the risks due to inhalation are greater for lower concentrations of I131 rather than for I129.

4.2 Socio-Environmental Database on GIS Platform

A database of the entire area of influence of CNAAA, especially within the emergency planning zones (EPZ), was developed and is composed of a GIS database that characterizes the several aspects taken into account in the research, among them those who most stand out are:

- Geological-geomorphological data, including landslides;
- Data on the environment, including: protected areas, fishing areas, vegetation areas, etc;
- Socioeconomic data such as population, land use, urban areas, institutions (schools, health centers, churches, etc.) and tourist areas;
- Among other information that make up local geographic area.

Figures 3 and 4 show the spatial distribution and the data structure incorporated in the information system adopted.

4.3 Meteogram with Data Observed from Tower A and Certain Results of Simulations with the WRF (Weather Research and Forecasting)

The analysis of the meteograms (Figure 5) on the data observed from Tower A and certain simulations with the WRF indicates a reasonable agreement regarding the wind intensity and direction for the first 15 hours. The greatest deviations between the simulated data and the data actually observed occurred after such time.

In the first 15 hours, the wind intensity was systematically lower than 2m/s and the simulation results indicated maximum values at the order of 3m/s. A similar trend is noted in the behavior of the variation of the wind intensity for the two databases, including a coincidence of the times of maximum and minimum intensity, as well as of the times when there was an increase and a decrease of such values. Regarding the wind direction, a slight deviation was noted between the datum observed and the simulated datum, with a predominance of winds in the N direction for the Tower A data and a predominance of winds at the NW sector for the data simulated with the WRF.

The simulations results indicate a trend of the WRF model to overestimate the wind intensity. In addition, deviations in the direction, especially in regions with complex terrains, are expected of simulations with mesoscale models. Thus, we considered the analysis on the radionuclide dispersion for the 15 hours of accidental release, especially due to the fact that the simulation results have better represented the region's wind field.

4.4 Radionuclide Concentration Scenarios obtained with the HYSPLIT Dispersion Model

Studies by Oliveira Júnior (2008), based on observational data from Towers A, B, C and D, installed at CNAAA's site, indicated a significant lack of homogeneity in the wind direction and intensity, especially due to the region's topographic complexity and the effect of land/sea breeze, which indicates limitations of the datum observed. Considering the identification of escape routes, it is important to

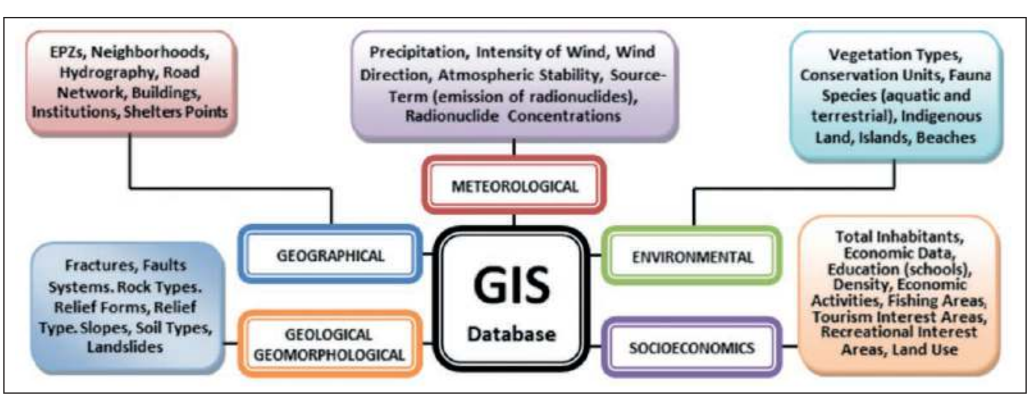

Figure 3 General structure of the GIS system created.

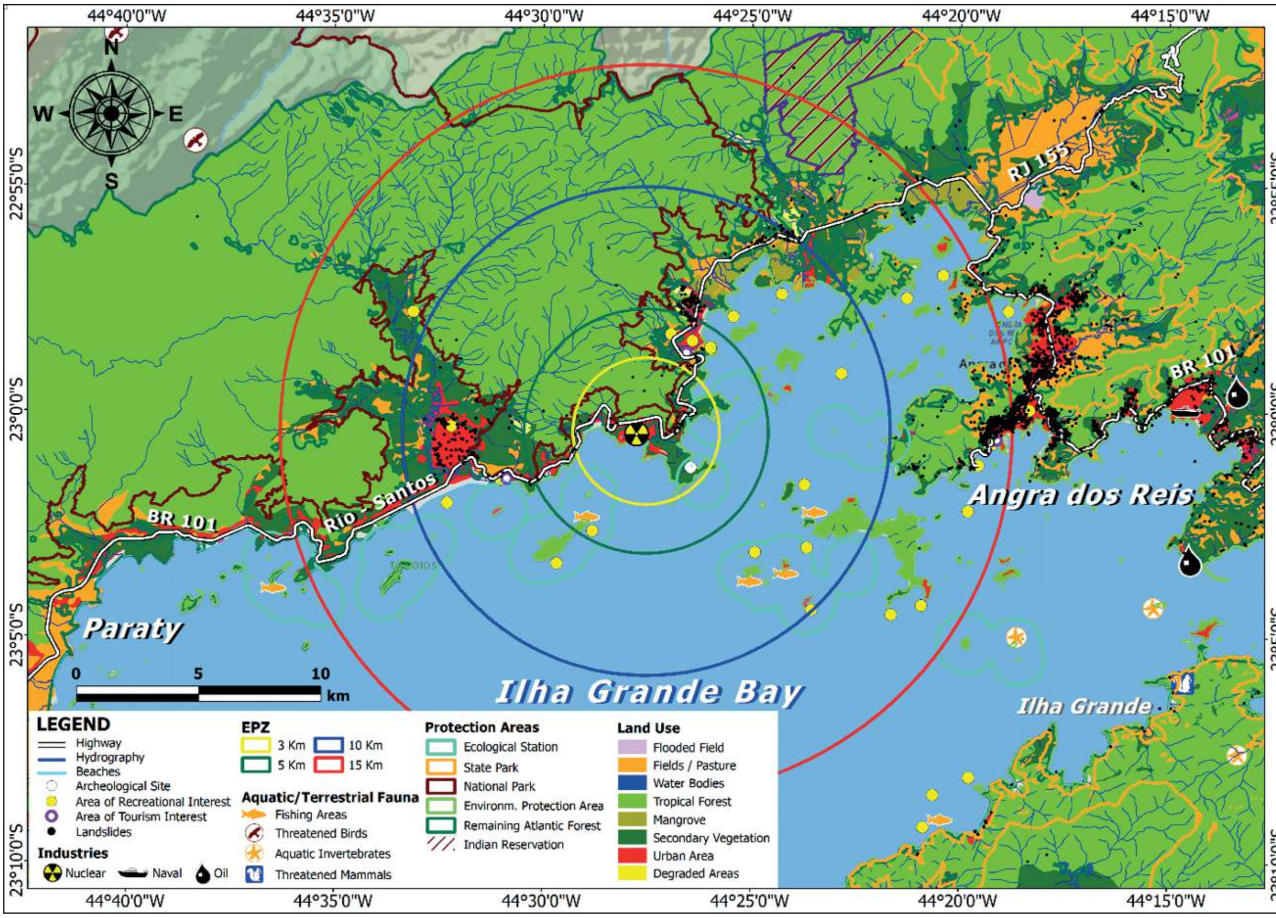

Figure 4 Map of socio-environmental data.

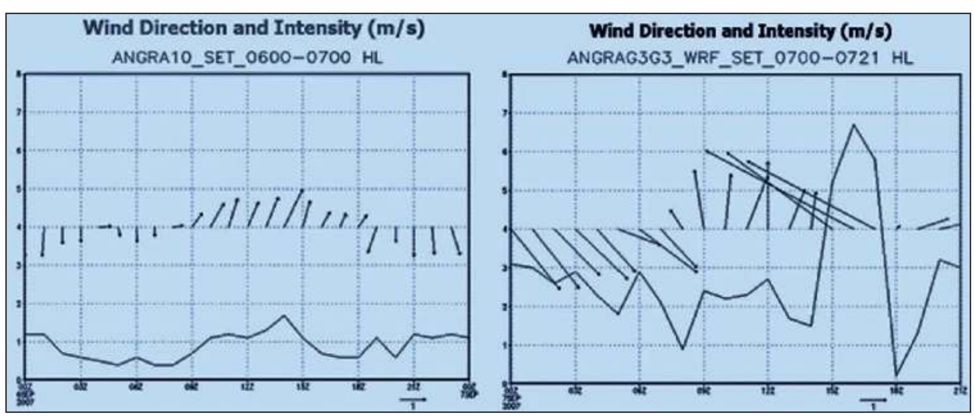

Figure 5 Meteogram of Wind Intensity and Direction Observed from Tower A and Meteogram of Wind Intensity and Direction Simulated with the WRF based on selected datum from Tower A.

incorporate vertically and horizontally specialized information, representing a more realistic modeling of the region's atmospheric conditions. Such need demonstrates the importance of the use of computer simulation of the atmosphere for the creation of evacuation plans, not only due to its prognostic nature but also due to the three-dimension atmospheric fields provided by the models, which could not have been obtained only by means of the data observed. In this regard, the WRF's three-dimension fields allow a better assessment of the temporal and spatial variation of the wind regime, in addition to supplying estimated results of the height of the boundary layer and atmospheric stability, which information is necessary to simulate the radionuclide dispersion in the HYSPLIT model, the maps of which show the simulations for I129 and I131, comparing the results only at the 0-5m and 120-160m levels.

Within 1 hour after the accident, the results for the levels from 0-5m, 5-40m, 40-80m to 80-120m indicated a negligible concentration, both for the I129 and for the I131. However, at the 120-160m level (Figure 6) the dispersion reached areas located within the EPZ 10, where Praia Brava, Praia Vermelha, Vila Histórica de Mambucaba, Perequê and Mambucaba (SW side), Frade and Vila do Frade (NE side) are located, as well as at the environs of the plant and certain isles at the Ilha Grande Bay. The evacuation of such areas would be compromised for whoever is located at the center of the plume. For the population located at the ends of the area of impact of the dispersion, the dislocation shall be respectively towards SW and NE, that is, those who are at the SW side shall be evacuated towards the city of Paraty and those located at the NE side shall go towards the center of the city of Angra dos Reis. The sheltering of the population is an important option for those located in the environs of the plant.

Three hours after the accident (Figure 7), the plume has reached the N/NE sector, reaching the proximities of the plant and the district of Frade, moving towards S/SW, arriving at Praia Brava, Praia Vermelha, Vila Histórica de Mambucaba, Perequê and Mambucaba, a large part of the Ilha Grande Bay and Trindade, at Paraty. The evacuation at that time is more feasible for those located at the ends of the areas, at the NE side. The sheltering of the population is indicated for those in the environs of the plant and in the communities of Praia Brava, Praia Vermelha, Vila Histórica de Mambucaba, Perequê and Mambucaba.

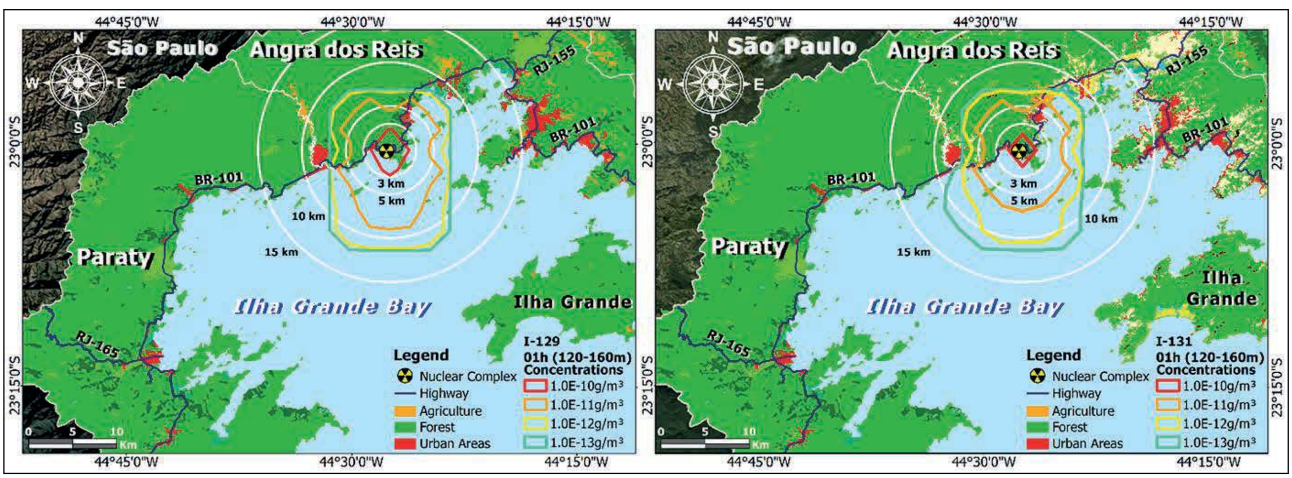

Figure 6 Scenario of the simulations for I129 and I131 within 1 hour after the accident - level from 120 to 160 m.

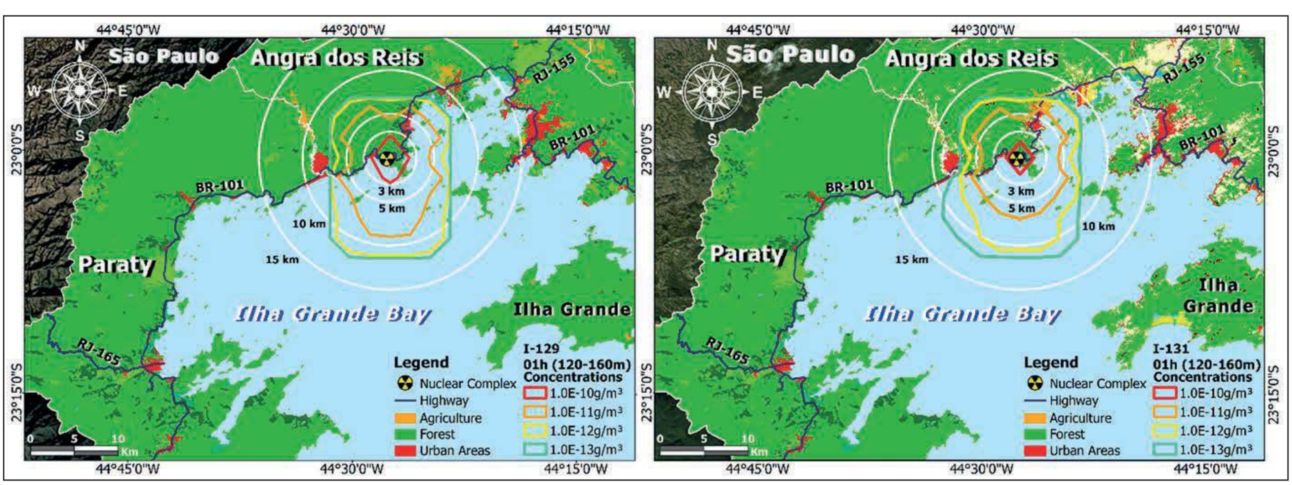

Figure 7 Scenario of the simulations for I129 and I131 within 3 hours after the accident - level from 0 to 05m and level from 120 to 160 m.

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Within 9 hours (Figure 8), the dispersion has had an impact on the SW sector, reaching areas close to the plant, Praia Brava, Praia Vermelha, Vila Histórica de Mambucaba, Perequê and Mambucaba, environs of Paraty and Trindade and a great part of the Ilha Grande Bay, at the S sector, parts of Ilha Grande and, at the NE sector, reaching the district of Frade, certain isles and the center of Angra dos Reis (level between 80 and 120m). In an evacuation, the SW direction would be totally affected, as well as by sea, and also at the NE side, where the region would only be clear beyond the district of Frade. The provision of shelters, in such scenarios, is the best option that could be adopted.

The period of 15 hours (Figure 9) has proven to be the most catastrophic, because at all levels the region has been affected, in all directions, reaching the center of Angra dos Reis – at the E-NE side; the Ilha Grande Bay – at the south – and reaching Paraty and Trindade at the W-SW part. Escape and evacuation routes are indicated only for those at the ends of such points, because for most of the population located within such areas, the best option is definitely to seek shelter.

5 Conclusions

The results on the radionuclide dispersion during the accidental release thereof allow a decision-making process based on real-time information, the success of which is associated to the ability of the WRF mesoscale model to represent the atmospheric phenomena that take place in the region and, consequently, the correct simulation of the wind scenario. In addition, the HYSPLIT air quality model must correctly simulate other radionuclide dispersion mechanisms: advection and turbulent diffusion, deposition processes and radioactive decay. These

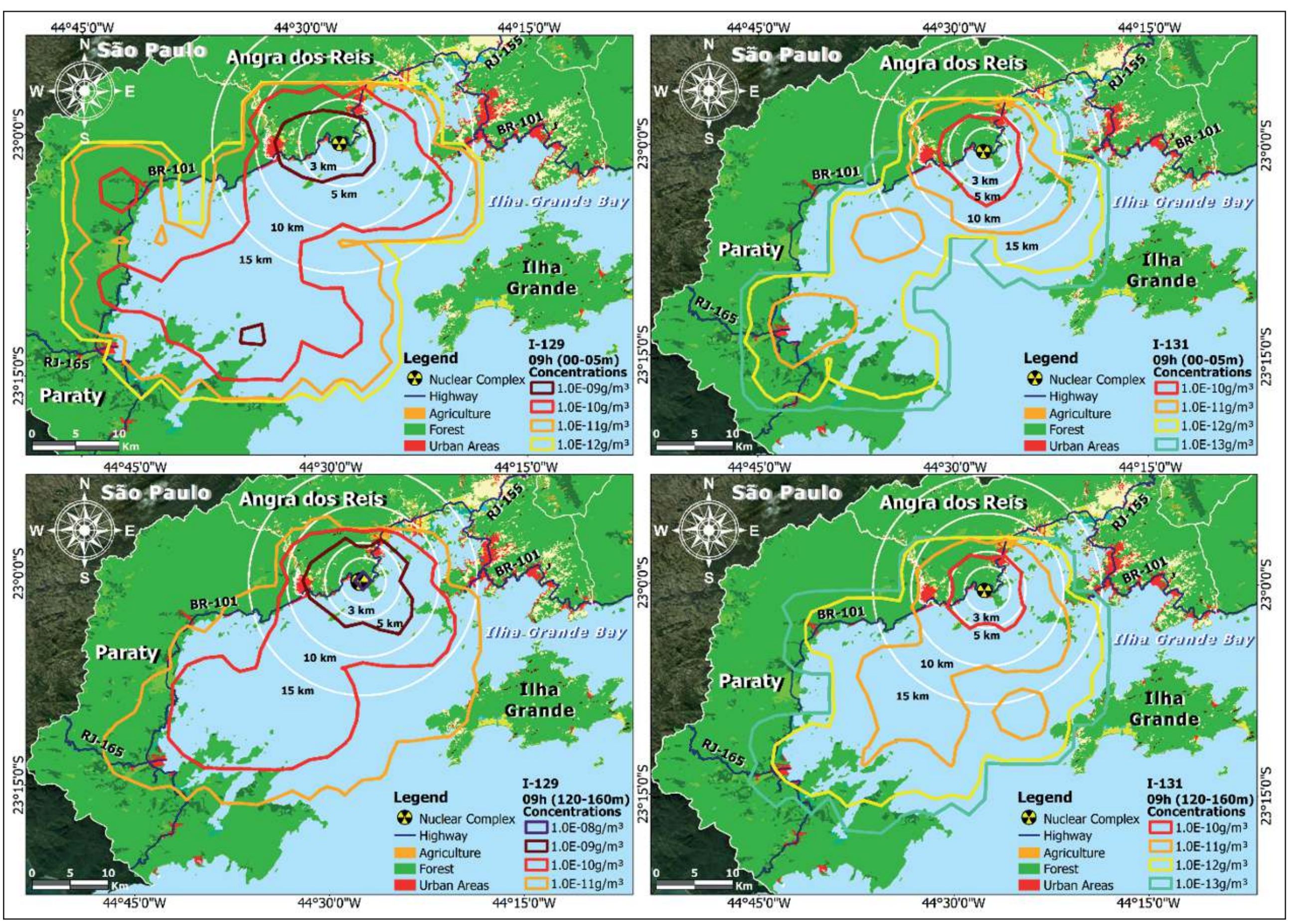

Figure 8 Simulations for I129 and I131 within 9 hours after the accident - level from 0 to 05m and level from 120 to 160 m.

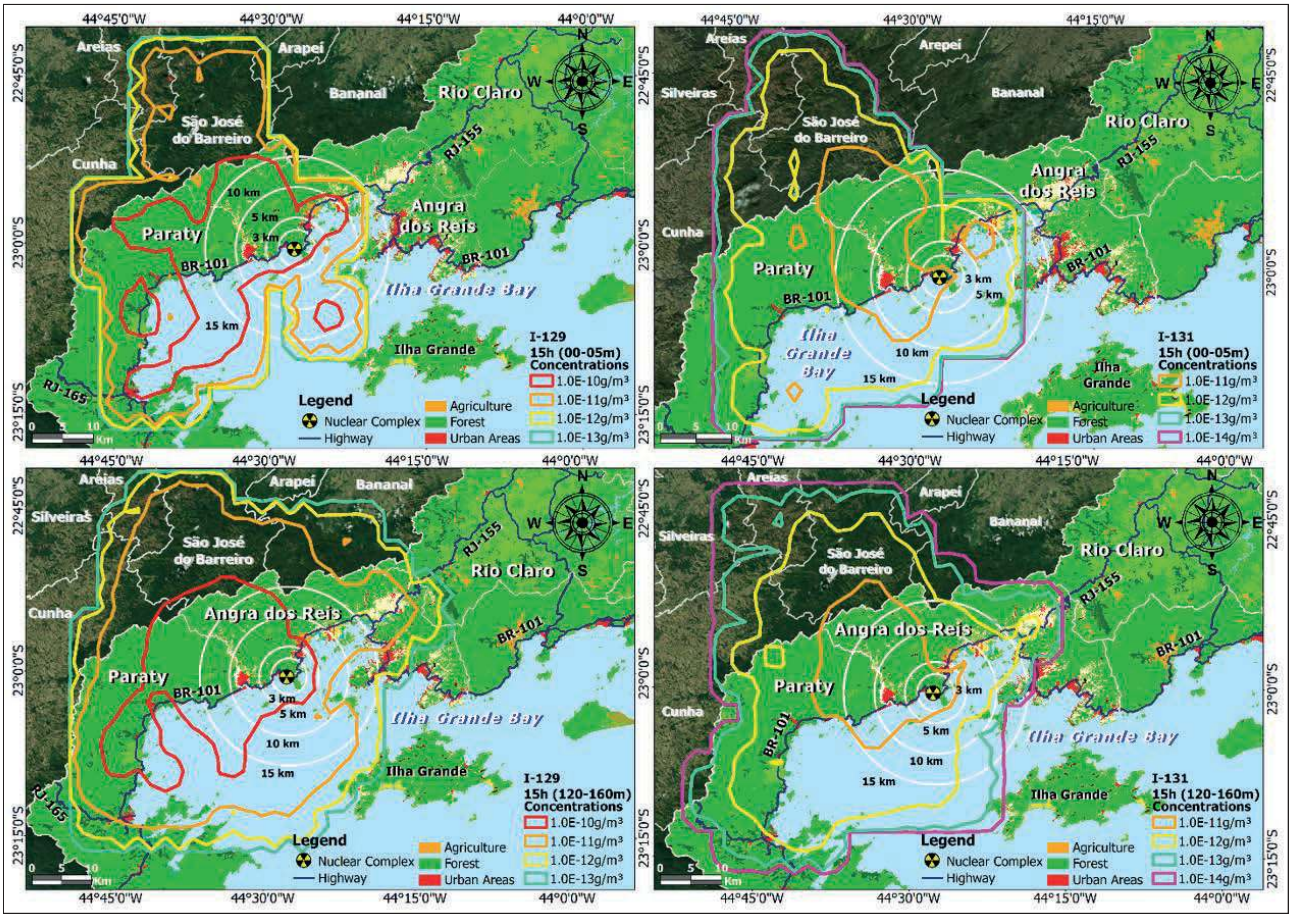

Figure 9 Scenario of the simulations for I129 and I131 within 15 hours after the accident - level from o to 05m and level from 120 to 160m.

needs demand that the CNAAA region and its environs to have an environmental monitoring network that allows the assimilation of data observed in the models used to assess the ability of the models to represent the phenomena that take place in the region, such as land/sea breeze, valley/mountain breeze, formation of an internal boundary layer, generation of mountain waves, etc. We stress the need to expand the surface meteorological network, including with the installation of sensors, such as sonic anemometers and global and incident radiation gauges, which will allow the determination of micro-meteorological parameters such as: friction speed, convective speed, height of the mixed layer, Monin-Obukhov length and Richardson number.

The results of the numeric modeling, associated to the real-time meteorological data, allow us to establish a more accurate diagnosis of the situation, in addition to the forecast of distribution of the concentration for the times subsequent to the beginning of the episode. The computer simulation results are also needed to assess the spatial scope of the impact of the radionuclide emission. This information is vital to establish the priority of the population evacuation area and the more vulnerable areas at every hour subsequent to the release of the pollutant by the CNAAA, which reinforces the need to obtain further details regarding the studied area and the representation of its phenomena based on the use of the combined WRF/HYSPLIT simulation system to estimate the radionuclide dispersion. The use of such models becomes important because it allows us to acquire knowledge on the temporal scale of the dispersion and the developments thereof, allowing one to design the planning of the emergency response and the local evacuation process.

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The radionuclide dispersion simulations conducted demonstrated that the risk levels shown for the I129 did not cause damages to the region. However, considering the emissions for the I131, the risks mostly showed average standards, with few areas where high and very high levels were reached. The simulations also showed the geographic complexity of the region, proving mainly that the geomorphologic configuration thereof, associated to the meteorological aspects, are important factors that influence the dispersion, as well as the emergency response proceeding, due to the difficulties posed by the relief in relation to the population escape routes in emergency situations, in addition to other conditioning factors that could aggravate such aspect, including traffic, rainfall dynamics and population increase.

GIS was an important tool applied in the representation of the diversity of the local geographic space, in the integration of the socio-environmental data and information collected, as well as in the aid to the analysis of the phenomena studied, by means of the spatialization of the information and the composition of a database for the region, which constitute a framework of elements that contribute to the continuity of the studies at the area and the furthering of associated matters, serving as grounds for the application thereof in related areas and studies.

The WRF and HYSPLIT models, together with GIS, served as basis for the spatial analysis and other interpretative analyses, assisting with the furthering of the scientific knowledge regarding the region. In this regard, the HYSPLIT was important to assess the dispersion and the simulated radionuclide concentration levels, including by determining the associated risks. In addition, the model represented the region's physical characteristics well, including: the topographic complexity, the wind scenario and the soil use categories. The WRF proved to be an atmospheric model with potential to be used in the studied region due to the possibility of representing atmospheric outflows in regions with complex terrains and under the effects of a land/sea breeze system. However, we must stress the need for further quantitative appraisal of the model's appropriateness for the region where the CNAAA is located, based on the comparison of the simulation results with the observational data obtained from the meteorological stations installed at the region. As is highlighted in the study, the correct simulation of the wind scenario during the radionuclide dispersion is crucial to identify areas that will be affected due to the advective transportation mechanism. Misleading information regarding such transportation, due to the local atmospheric circulation, can lead to an ineffective decision-making process for the planning of the evacuation of the area.

Simplified data on the source term were important to understand the complexity that involves the radionuclide simulation process, as well as the relevance of the characteristics of the accident and the main elements thereof: emission rate, quantity emitted, fuel fusion temperature and kinds of radionuclides.

The study has shown that many elements are still lacking, which elements are important to aid in the decision-making process for the planning of the emergency response in the region. Several of them are fundamental to subsidize the application of a set of actions intended to manage the risks associated to nuclear power within the area under the influence of the CNAAA. In this regard, the implementation of several of such measures shows the concern with the local physical, social and economic environment, and is a proactive step towards presenting actions to attempt to decrease the uncertainties and insecurity that such activity and the enterprise cause, especially to the population.

The study also pointed out other results, such as the combined assessment involving wind scenario climatology knowledge, the radionuclide dispersion computer simulation results and information on the landslide risk areas, which are typical in the area. Thus, the shared analysis of the emergency response planning and the evacuation process can be made for a short-term and a long-term planning, as described by Silva (2013). Such matters are important and shall be subject to a more in-depth analysis in subsequent publications.

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7 References

Draxler, R.R & Rolph, G.D. 2003. Hybrid single-particle Lagrangian integrated trajectory (HYSPLIT) Model. NOAA Air Resources Laboratory, Silver Spring, MD. Available at: < http://www.arl.noaa.gov/ready/hysplit4.html>. Accessed: 18/04/2018.

Freitas, C.M. 1996. *Acidentes Químicos Ampliados – Incorporando a Dimensão Social nas Análises de Riscos*. Programa de Saúde Pública, Escola Nacional de Saúde Pública, Fundação Oswaldo Cruz, Tese de Doutorado, 243p.

Freitas, C.M, Porto, M.F.S. & Gomez, C.M. 1995. Acidentes Químicos Ampliados: Um Desafio para a Saúde Pública. *Revista Saúde Pública*, *29*(6): 503-514.

Gonçalves Júnior, M.A. 2006. *Aplicação da Fluidodinâmica Computacional à Dispersão Atmosférica de Radionuclídeos na Vizinhança de uma Central Nuclear*. Programa de Pós-Graduação do Instituto de Engenharia Nuclear, Instituto de Engenharia Nuclear, Comissão Nacional de Energia Nuclear, Dissertação de Mestrado, 86p.

Haguenauer, L. 1986. *O Complexo Químico Brasileiro: Organização e Dinâmica Interna*. Rio de Janeiro, RJ: Ed. Instituto de Economia Industrial / UFRJ. 112p.

IBGE. 2010. Instituto Brasileiro de Geografia e Estatística. *Censo Demográfico 2010*. Rio de Janeiro. Disponível em: < https://www.ibge.gov.br>. Acesso em: 18/04/2018.

IBGE. 2017. Instituto Brasileiro de Geografia e Estatística. *Brasil em Síntese: Panorama*. Rio de Janeiro. Disponível em: < https://www.ibge.gov.br> Acesso em: 18/04/2018.

MRS Estudos Ambientais Ltda. 2006. *Estudo de Impacto Ambiental da Unidade 3 da Central Nuclear Almirante Álvaro Alberto*. Disponível em: <http://www.eletronuclear.gov.br/hotsites/eia/index.html>. Acesso em 18/04/2018.

Oliveira Jr, J.F. 2008. *Estudo da Camada Limite Atmosférica na Região de Angra dos Reis através do Modelo de Mesoescala MM5 e Dados Observacionais*. Programa de Engenharia Civil, COPPE, Universidade Federal do Rio de Janeiro, Tese de Doutorado, 244p.

Quarantelli, E.L. 2000. Principais Critérios para Avaliar o Planejamento de Emergência e a Gestão de Desastres e sua Aplicabilidade nas Sociedades em Desenvolvimento. *In*: HERCULANO, S.; PORTO, M.F.S.; FREITAS, C.M. (org.). *Qualidade de Vida & Riscos Ambientais*. EdUFF, p. 171-215.

Silva, C. 2013. *Modelagem Lagrangeana da Dispersão Atmosférica de Radionuclídeos e Sistemas de Informação Geográfica como Ferramentas de Suporte ao Planejamento de Emergência na Área de Influência do Complexo Nuclear de Angra dos Reis - RJ*. Programa de Engenharia Civil, COPPE, Universidade Federal do Rio de Janeiro, Tese de Doutorado, 251p.

Silva, C; Landau, L.; Pimentel, L.C.G. & Heilbron Filho, P.F.L. 2013. GIS as a Decision Support Tool in the Area of Influence of the Nuclear Complex Angra dos Reis, Brazil. *Journal of Geographic Information System*, *5*: 13-23.

Silva, C. 2007. *Mapeamento na Área de Influência em Refinaria de Petróleo Apoiado em Sistemas de Informação Geográfica como Suporte ao Planejamento de Ação em Emergências*. Programa de Engenharia Civil, COPPE, Universidade Federal do Rio de Janeiro, Dissertação de Mestrado, 97p.

Soares, E.P. 2006. *Caracterização da Precipitação na região de Angra dos Reis e a sua relação com a ocorrência de Deslizamentos de Encostas*. Programa de Engenharia Civil, COPPE, Universidade Federal do Rio de Janeiro, Dissertação de Mestrado, 145p.

Souza Júnior, A.B. 2002. *Sistemas de Resposta para Acidentes Industriais com Consequências Externas - Experiência Internacional e Situação Brasileira*. Programa de Planejamento Energético, COPPE, Universidade Federal do Rio de Janeiro, Tese de Doutorado, 200p.