IDENTIFICATION OF EVACUATION ZONES BY SUPERPOSED HAZARD MAPPING METHOD IN CASE OF A HYPOTHETICAL NUCLEAR POWER PLANT ACCIDENT: THE CASE OF AKKUYU NUCLEAR POWER PLANT

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ABSTRACT

IDENTIFICATION OF EVACUATION ZONES BY SUPERPOSED HAZARD MAPPING METHOD IN CASE OF A HYPOTHETICAL NUCLEAR POWER PLANT ACCIDENT: THE CASE OF AKKUYU NUCLEAR POWER PLANT

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The capacity of ionizing radiation to cause severe damage leads to a growing concern worldwide, raising awareness to protect the living and non-living environment against nuclear disasters with efficient preparation and response. Evacuation planning plays an essential role in avoiding and mitigating the adverse effects of this radiation. This research aims to identify evacuation zones and estimate evacuation demand by developing superposed nuclear hazard maps on a GIS platform for the hypothetical accident scenario in Akkuyu Nuclear Power Plant (Akkuyu-NPP). It assumes a hypothetical nuclear power plant accident sequence, bringing about in-vessel core melting. Using HySPLIT, the research simulates the atmospheric dispersion models of Cesium-137 and lodine-131 in three different meteorological conditions (cold, warm and hot climate conditions) that can be observed in the Mersin region. The atmospheric dispersion models show the spatiotemporal progress of the critical threshold value of 1 mSv/hr determined by the International Atomic Energy Agency (IAEA). The research creates nuclear hazard maps for the first 72-

hour time window by using the map overlay technique in ArcMap. Subsequently, it develops an integrated geographical database to model radiation exposure risk based on the total exposure time and thereby identifies the vulnerability level of the areas to radiation. Spatially introducing the neighborhoods' populations in the risk zones, it generates thematic maps to observe the spatial distribution of evacuation demand for each scenario within the evacuation zones. Consequently, this research provides the initial steps of evacuation planning in the emergency preparedness phase for the hypothetical accident in the Akkuyu-NPP. In this way, it guides the nuclear emergency preparedness and evacuation planning process to the emergency responders and decision-makers in Turkey to prevent potential casualties and injuries, minimize radiation exposure to the public and the environment, and mitigate the future effects of radiation.

Keywords: Akkuyu Nuclear Power Plant, HySPLIT, GIS, Superposed Hazard Mapping, Evacuation Zones

ÖZ

VARSAYIMSAL BİR NÜKLEER ENERJİ SANTRALİ KAZASI DURUMUNDA ÜST ÜSTE KONUMLANDIRILMIŞ AFET HARİTALAMASI YÖNTEMİ İLE TAHLİYE BÖLGELERİNİN BELİRLENMESİ: AKKUYU NÜKLEER ENERJİ SANTRALİ ÖRNEĞİ

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İyonlaştırıcı radyasyonun ciddi hasara neden olma kapasitesi, dünya çapında artan bir endişeye yol açmaktadır ve bu endişe, canlı ve cansız çevreyi nükleer felaketlere karşı etkin hazırlık ve müdahale ile koruma bilincini artırmaktadır. Bu radyasyonun olumsuz etkilerini önlemede ve hafifletmede, tahliye planlaması önemli rol oynamaktadır. Bu araştırma, Akkuyu Nükleer Güç Santrali'ndeki (Akkuyu-NGS) varsayımsal bir kaza senaryosu için CBS platformunda süperpoze nükleer tehlike haritaları geliştirerek tahliye bölgelerini belirlemeyi ve tahliye talebini tahmin etmeyi amaçlamaktadır. Bu araştırma, çekirdek erimesiyle sonuçlanan varsayımsal bir nükleer santral kazası dizisinin olduğunu varsaymaktadır. Mersin Bölgesi’nde gözlemlenen üç farklı meteorolojik koşulda (soğuk, ılık ve sıcak iklim koşullarında), Sezyum-137 ve İyot-131’in atmosferik dağılımını HySPLIT kullanarak modellemektedir. Atmosferik dağılım modelleri, Uluslararası Atom Enerjisi Ajansı (IAEA) tarafından belirlenen 1 mSv/saatlik kritik eşik değerinin uzaysal-zamansal ilerlemesini göstermektedir. Araştırma, ArcMap’deki harita çakıştırma tekniği kullanılarak ilk 72 saatlik zaman dilimi için nükleer risk haritaları oluşturmaktadır.

Ardından, toplam radyasyona maruz kalma süresine dayalı olarak, radyasyon maruz kalma riskini modellemek için bütünleşik bir coğrafi veri tabanı geliştirerek, alanların radyasyona karşı savunmasızlık düzeyini belirlemektedir. Risk bölgelerindeki mahallerin nüfuslarını mekânsal olarak tanıtarak, tahliye bölgeleri içindeki her bir senaryo için tahliye talebinin mekânsal dağılımını gözlemlemeyi sağlayan tematik haritalar oluşturmaktadır. Sonuç olarak, bu araştırma Akkuyu-NGS'deki varsayımsal bir kaza için acil durum hazırlık aşamasında tahliye planlamasının ilk adımlarını göstermektedir. Böylece, araştırma, olası can ve mal kayıplarının ve yaralanmaların önlenmesi, halkın ve çevrenin maruz kalacağı radyasyonun en aza indirilmesi ve radyasyonun gelecekteki etkilerinin azaltılması için Türkiye'deki acil müdahale ekiplerine ve karar vericilere nükleer acil durum hazırlık ve tahliye planlama sürecine rehber etmektedir.

Anahtar Kelimeler: Akkuyu Nükleer Enerji Santrali, HySPLIT, CBS, Süperpoze Afet Haritalaması, Tahliye Bölgeleri

To my beloved family

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ABBREVIATIONS

AKKUYU-NPP: Akkuyu Nuclear Power Plant

ARL: Air Resources Laboratory

CNPP: Country Nuclear Power Profile

DEMA (AFAD in Turkish): Disaster and Emergency Management Authority

EAL: Emergency Action Levels

ECCS: Emergency Core Cooling System

EIA: Environmental Impact Assessment

FEMA: Federal Emergency Management Agency

GDAS: Global Data Assimilation System

HySPLIT: Hybrid Single-Particle Lagrangian Integrated Trajectory

IAEA: International Atomic Energy Agency

ICRP: International Commission on Radiological Protection

INES: International Nuclear and Radiological Event Scale

LBLOCA: Large Break Loss-of-Coolant Accident

NRA: Nuclear Regulatory Authority

NOAA: National Oceanic and Atmospheric Administration

OIL: Operational Intervention Level

PIE: Postulated Initiating Events

SBO: Station Blackout

TAEA: Turkish Atomic Energy Authority.

UNDRR: United Nations Office for Disaster Risk Reduction

UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation

US-NRC: The United States Nuclear Regulatory Commission

VVER: Water-water Energetic Reactor

CHAPTER 1

INTRODUCTION

Nuclear power plants (NPPs) are facilities that convert nuclear fission energy into electrical energy (Donev et al. (2021). They are preferable since they produce very high amounts of electrical energy and do not release carbon into the air (US EIA, 2021); thus, they are assumed to be effective and "nature-friendly" energy production facilities. However, there is always the risk of a nuclear power plant accident. There have been recorded at least 99 civilian and military nuclear power plant accidents with different damage levels from 1952 to 2010 (Sovacool, 2010); devastating results of some of them (i.e., Chernobyl, Fukushima, etc.) are still being observed. Thus, there have been regulations with countermeasures developed for such cases, mostly at the national level.

1.1 Evacuation Planning Need for Nuclear Disasters

The potential accidents in nuclear power plants (design-based and beyond-design-based) can only be foreseen to some extent. All severe nuclear power plant accidents were due to unforeseen sequences in history (Arnold et al., 2011). Although the probability of a severe nuclear accident in the nuclear power plant is regarded as low, the damage that will cause can be extreme. For this reason, 'postulated initiating events' (PIEs) are defined to predict the likelihood of an unforeseen nuclear accident and the potential consequences. It is possible to define various scenarios by considering the PIEs to protect the public from the severe consequences of radioactive fallout. Therefore, in case of an unforeseen nuclear accident in a nuclear power plant, the main aim of emergency planning is to minimize radiation exposure to humans and evacuate the population in danger from possible hazard zones.

Evacuation is the process of moving the population away from a dangerous place to a safe location, and it is the most effective countermeasure requiring a proper plan in nuclear power plant emergencies. Evacuation planning is a procedure indicating the evacuation process and plays an essential role in avoiding and mitigating the negative effects of radiation exposure. Since the 1980s, it has been stipulated to have an evacuation plan as the must component of nuclear emergency planning and management in countries with nuclear power to minimize the radiation exposure and effects on future generations and to prevent potential casualties and injuries.

1.2 Problem Statement and Aim of the Research

Throughout history, Turkey has made various attempts to construct a nuclear power plant, finalized in 2010 with the agreement between Turkey and the Russian Federation to construct Turkey's first nuclear power plant in the Akkuyu field of Mersin province. Turkey's first NPP, the Akkuyu Nuclear Power Plant (abbreviated hereafter as Akkuyu-NPP), started to be constructed in 2013. The plant's first unit is expected to be completed and will start to operate in 2023. The last unit of the nuclear power plant is estimated to be finalized and start operating in 2026. Nevertheless, the current regulations, plans, and reports explaining the actions and precautions for nuclear power plant emergencies in Turkey do not include detailed and sufficient information about evacuation planning in case of nuclear emergencies. However, unfortunate events may occur in the Akkuyu-NPP. The strong meteorological winds in the Mersin region necessitate the determination of an evacuation demand size and distribution in the possibility of an accident/malfunction at the Akkuyu-NPP. This research considers the possibility of unfortunate event sequences that may happen in Akkuyu-NPP and presents the radiation exposure zones, including evacuation demand, with superposed nuclear hazard maps to reveal the importance of having a comprehensive evacuation plan for nuclear power plant emergencies.

This research aims to identify evacuation zones and spatial distribution of evacuation demand by developing superposed nuclear hazard maps using GIS for the hypothetical accident in Akkuyu -NPP. A hypothetical nuclear power plant accident sequence is assumed to result in in-vessel core melting, in which case atmospheric dispersion of Cesium-137 and Iodine-131 was modeled by HySPLIT with a constant source term for three major meteorological conditions observed in the region. The spatiotemporal progress of the critical threshold value of 1 mSv/h for evacuation determined by the IAEA and the value of 0.5 mSv/h determined by this research as a possible evacuation threshold is extracted from atmospheric dispersion models. Furthermore, hazard maps for a nuclear disaster scenario were created for the first 72-hour time window in ArcMap by using the spatial overlay technique to create an integrated geo-database on radiation hazard zones for the subsequent use in modeling radiation exposure risk based on the total exposure time to identify the vulnerability of areas to radiation. Introducing the populations of the neighborhoods in the risk zones, a thematic map was generated for the distribution of evacuation demand for each scenario superposed with the spatiotemporal progress of the disaster zone.

1.3 Expected Contribution of Research

This research is interdisciplinary as it contributes to various disciplines, such as nuclear emergency planning, evacuation planning, geography, transportation planning, and urban planning. There is a lack of evacuation studies for nuclear power plants in Turkey. This research aims to fill this gap by providing the first steps of evacuation planning for nuclear power plants with a special focus on the Akkuyu-NPP in Turkey. This thesis contributes to the literature on evacuation studies by using a research method that combines the atmospheric dispersion model findings of a hypothetical accident sequence and the nuclear hazard mapping to estimate the evacuation zones under three different meteorological conditions. Besides, this research integrates the evacuation planning steps with Esri’s ArcMap spatial data handling tools to provide responsible authorities with all the relevant information to use and prioritize in evacuation planning and reveal the insufficiencies requiring improvement. In broader application, this thesis furthers our understanding of the evacuation process during nuclear power plant accidents, especially in Turkey, to protect the public and future generations from radiation by producing planning policies derived from the output of such research.

1.4 Limitations

For the development of a hypothetical nuclear power plant accident sequence, it is assumed that

- a radiation release that can start from the Large Break Loss of Coolant (LBLOCA) accident and
- result in in-vessel core melting in nuclear power plant
- followed by atmospheric dispersion of Cesium-137 and Iodine-131

The accident was modeled by HySPLIT for three major meteorological conditions observed in the region. The atmospheric dispersion is modeled only for a cloud-shine pathway. The selected meteorological data affecting the atmospheric dispersion does not include any kind of precipitation. The radioactive plume includes only Cesium-137 and Iodine-131.

- ➢ The dose conversion factor is for an 'adult reference person' defined by the IAEA. The default threshold value for evacuation is 1 mSv/h calculated by the IAEA considering an unshielded person who has been exposed to the plume for 4 hours. As a second threshold, an effective dose rate of 0.5 mSv/h is also monitored as a critical limit beyond which a "safe" limit can be drawn to define possible evacuation destinations.

Three scenarios with different weather conditions were selected based on the yearly distribution of wind directions and levels published by the Global Data Assimilation System and assumed to happen at

- Scenario 1: 12.00 pm 08 February 2021
- Scenario 2: 12.00 pm 15 May 2021
- Scenario 3: 12.00 pm 01 December 2021.

The IAEA defines various countermeasures for nuclear disasters to minimize radiation exposure, such as using iodine prophylaxis, shelter-in-place, evacuation, and relocation. These countermeasures necessitate different threshold values to be implemented. This research only considers evacuation as the countermeasure applied for nuclear power plant accidents, and the population affected by the radioactive plume is the only address-based population for the evacuation demand estimation.

1.5 Organization of Thesis

The thesis layout is as follows: Chapter 1 includes a brief explanation of the scope of this research with the problem definition and research goals. Then, it implies why this research is important and how it contributes to the literature. After that, limitations generating the research frame are listed, and the thesis organization is given.

Chapter 2 provides background information to understand the research topics and concepts. In general, it explains the historical development of nuclear energy and nuclear power plants in the world and basic concepts related to the regulatory framework of radiation protection and emergency preparedness worldwide. Then, it defines the atmospheric dispersion modeling with the potential exposure pathways, the possible health effects of selected radioactive materials, and the selected model information for this research. Lastly, it describes the importance of evacuation planning in the emergency preparation process for nuclear power plant accidents and explains evacuation planning steps.

Chapter 3 provides the historical development and regulatory framework of nuclear energy in Turkey, and the site analysis of the study area, Akkuyu-NPP vicinity, with the basic information necessary for evacuation.

Chapter 4 explains the methodology of this research. As a first step, it explains the hypothetical scenario and input parameters for atmospheric dispersion modeling and the ambient dose rate assessment with the sensitivity analysis for the HySPLIT.

Then, it explains the nuclear hazard mapping process and initial steps of evacuation planning for Akkuyu-NPP.

Chapter 5 presents the actual atmospheric dispersion model results, overlapped hazard maps, and risk classification of evacuation zone by ambient dose rate. Besides, it analyzes and compares the total affected area size and population by radioactive plume within the evacuation zone. Furthermore, it discusses the effects of meteorological data on the dynamic progress of evacuation zones and demand, the effects of possible risk zone on evacuation demand and process and provides recommendations for Akkuyu-NPP evacuation planning.

Chapter 6 overviews the conclusion of this research and provides recommendations for future studies and policy recommendations for evacuation planning as guidance.

CHAPTER 2

LITERATURE REVIEW

The following chapter provides background information to understand the research topics and concepts. It explains the historical development of nuclear energy in the world and the regulatory framework of radiation protection and emergency preparedness. Further, it describes the atmospheric dispersion modeling with the necessary parameters. Lastly, it gives evacuation planning steps for nuclear power plant accidents. These topics provide fundamental information forming the basis of this research.

2.1 Historical Development of Nuclear Energy and Nuclear Power Plants (NPPs)

Nuclear power plants (NPPs) are established facilities that convert the energy released by nuclear fission into electrical energy (Donev et al., 2021). The basic operational process of nuclear power plants with PWR-type reactor units (see Figure 2.1) follows: The uranium (the dominant fuel choice in the world today) in the reactor's core is split into nuclei of atoms, and very-high heat is released. The heat generated in the reactor is transferred to the pressured water and then to the steam generator with the help of pumps and pipes. The produced steam spins a turbine connected to a generator that produces electricity (Donev et al., 2021).

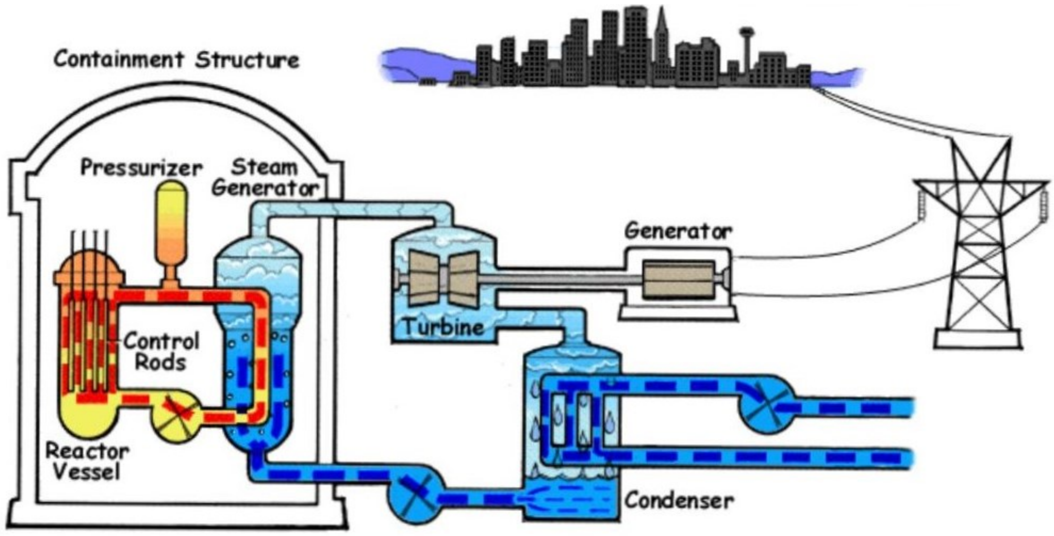

Figure 2.1. The basic operation of a nuclear power plant with PWR type reactor. (Mouginot & Hänninen, 2013, p.4)

At the beginning of the 20th century, the science of atomic radiation, atomic change, and nuclear fission was developed. Between 1939 and 1945, the main focus of studies on nuclear power was on atomic bombs because of the on-going World War II. After 1945, scientists started to work to benefit from nuclear energy in a controlled manner to generate electricity (WNA, 2020)· On September 3rd, 1948, a nuclear reactor produced electricity for the first time at the X-10 Graphite Reactor in Oak Ridge, Tennessee, in the USA. From the first attempt to use nuclear power for electricity production, the prime focus has evolved on the technological development of reliable nuclear power plants. The world's first nuclear power plant started operations in Obninsk, Moscow, on June 27th, 1954 (Ichikawa, 2016).

NPPs are preferable since they produce very high amounts of electrical energy and do not release carbon into the air (US EIA, 2021); thus, they are assumed to be effective and "nature-friendly" energy production facilities. Since the first nuclear power plant constructed, the interest in using nuclear power plants to generate electricity has been grown. Nuclear Power Plants produce around 11% of electricity worldwide; the USA and France are the most prominent producers. (Donev et al., 2021). As of 2020, the International Atomic Energy Agency (IAEA) reported that

441 nuclear power reactors are in operation, and 54 nuclear power reactors are under construction worldwide (IAEA, 2020).

2.1.1 Nuclear Power Plant Accidents in History

People have faced the devastating effects of nuclear power plants throughout history. The results of some devastating accidents are still ongoing. At least 99 civilian and military nuclear power plant accidents have been recorded with different damage levels between 1952 and 2010 (Sovacool, 2010). In the 1980s, after some accidents in nuclear facilities, the need for activities against radiation risks arose. The IAEA and the Organization for Economic Co-operation and Development Nuclear Energy Agency (OECD/NEA) developed the International Nuclear and Radiological Event Scale (INES) in 1990 to make communication on radiation risks consistently. (IAEA & OECD/NEA, 2008).

According to the INES, nuclear events are classified at seven levels, collected in two groups (see Figure 2.2). Events with levels 1-3 are considered as the events with less safety significance and are called 'incidents.' Events with levels 4-7 are defined as the events with more considerable safety significance, and they are called 'accidents'. Finally, events without safety significance are determined as below scale/ level 0 and called 'deviations'. Furthermore, the severity of an event is identified as ten times more for each increase in level (IAEA & OECD/NEA, 2008)

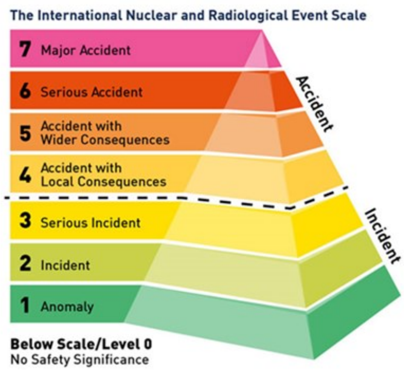

Figure 2.2. International Nuclear and Radiological Event Scale. (US NRC, 2017)

Some of the examples of nuclear power plant accidents with an INES level greater than or equal to 4 are shown in Table 2.1, and the most known accidents are explained in the following:

- On March 28th, 1979, the most significant accident in the USA commercial nuclear power plant history occurred at the Three Mile Island Nuclear Power Plant. According to the INES, the Three Mile Island accident caused by a partial meltdown in the core reactor was rated as level 5 (IAEA & OECD/NEA, 2008).
- On April 26th, 1986, the Chernobyl disaster, considered the world's worst nuclear accident, occurred in the Soviet Union. A safety test on a nuclear reactor resulted in an explosion and fire, and a massive amount of radiation spread into the atmosphere. According to INES, the Chernobyl Nuclear Power Plant accident is one of two accidents determined as level 7 (IAEA & OECD/NEA, 2008).
- Another disaster rated as a level 7 event on the INES is the Fukushima Daiichi nuclear disaster. On March 11th, 2011, the 9.0 magnitude earthquake and 14-meter-high tsunami generated by an earthquake hit eastern Japan. It led to three nuclear meltdowns, three hydrogen explosions, and a large amount of radiation release (IAEA & OECD/NEA, 2008). The Fukushima Daiichi Nuclear Power Plant Accident Report by IAEA (2015) provides detailed information about the process of the accident and the implementation of protective actions. According to this report (2015), the decisions on protective actions were based on the projected dose to the public estimations calculated using a dose projection model, namely the System for Prediction of Environmental Emergency Dose Information (SPEEDI), at the time of the accident. National emergency arrangements were based on plant conditions in response to the accident; however, the source term estimations could not be provided as input to SPEEDI due to the loss of on-site power. The evacuation of people from the Fukushima Daiichi NPP vicinity began on the evening of March 11th, 2011, with the 2 km radius evacuation zone and

gradually extended to 3 km and then to 10 km (See Figure 2.3). By the evening of March 12th, the evacuation zone extended to 20 km, and the public in the area within 20-30 km was ordered shelter-in-place on March 15th until the national government recommended voluntary evacuation on March 25th. On April 22nd, the existing 20 km evacuation zone was assigned as a 'Restricted Area,' with controlled re-entry, and the area beyond was assigned as a 'Deliberate Evacuation Area' in considering the dose criteria for relocation might be exceeded. As a result of the implemented protective actions in response to the accident, the administration of iodine tablets was not implemented uniformly owing to the lack of detailed arrangements, and the evacuation and sheltering zones were modified several times within 24 hours due to difficulties in coordination and insufficient pre-planning.

Table 2.1 *13 nuclear power plant accidents with an INES level greater than or equal to 4. (Ha-Duong & Journe, 2014, p.8)*

Date	City	Country	Reactor	INES	Description
1966-10-05	Newport	USA	Unit 1	4	Two fuel assemblies out of 105 melted
1967-05-01	Chapelcross	UK	Unit 2	4	Fuel element melt and fire in part of core
1969-10-17	Saint Laurent	France	Unit 1	4	Partial (approximately 50 kg U) core melt during loading
1974-02-06	Leningrad	Russia	Unit 1	4	Secondary circuit rupture-3 fatalities
1975-11-30	Leningrad	Russia	Unit 1	4	Power excursion + partial core melt + atmospheric release
1977-01-01	Beloyarsk	USSR	ABM-200	5	Unit 2-half core melt
1977-02-22	Jaslovske Bohunice	Slovakia	A1	4	Refueling accident + corrosion + primary and secondary circuits contamination
1979-01-02	Three Mile Island	USA	Unit 2	5	Reactor core melt
1980-03-13	Saint Laurent	France	Unit 2	4	Partial (approximately 20 kg U) core melt
1982-09-09	Tchernobyl	Ukraine	Unit 1	4	Partial core melt - fuel assembly channel 62-44 destroyed
1968-04-26	Tchernobyl	Ukraine	Unit 4	7	Criticality accident + fire + steam explosion
1989-11-24	Greifswald	Germany	Unit 5	4	Near core melt - 10 fuel elements damaged
2011-04-12	Fukushima Daiichi	Japan	Units 1, 2, 3	7	Multiple core damage by loss of all cooling function

INES level for events before 1991 has been assessed according to INES criteria

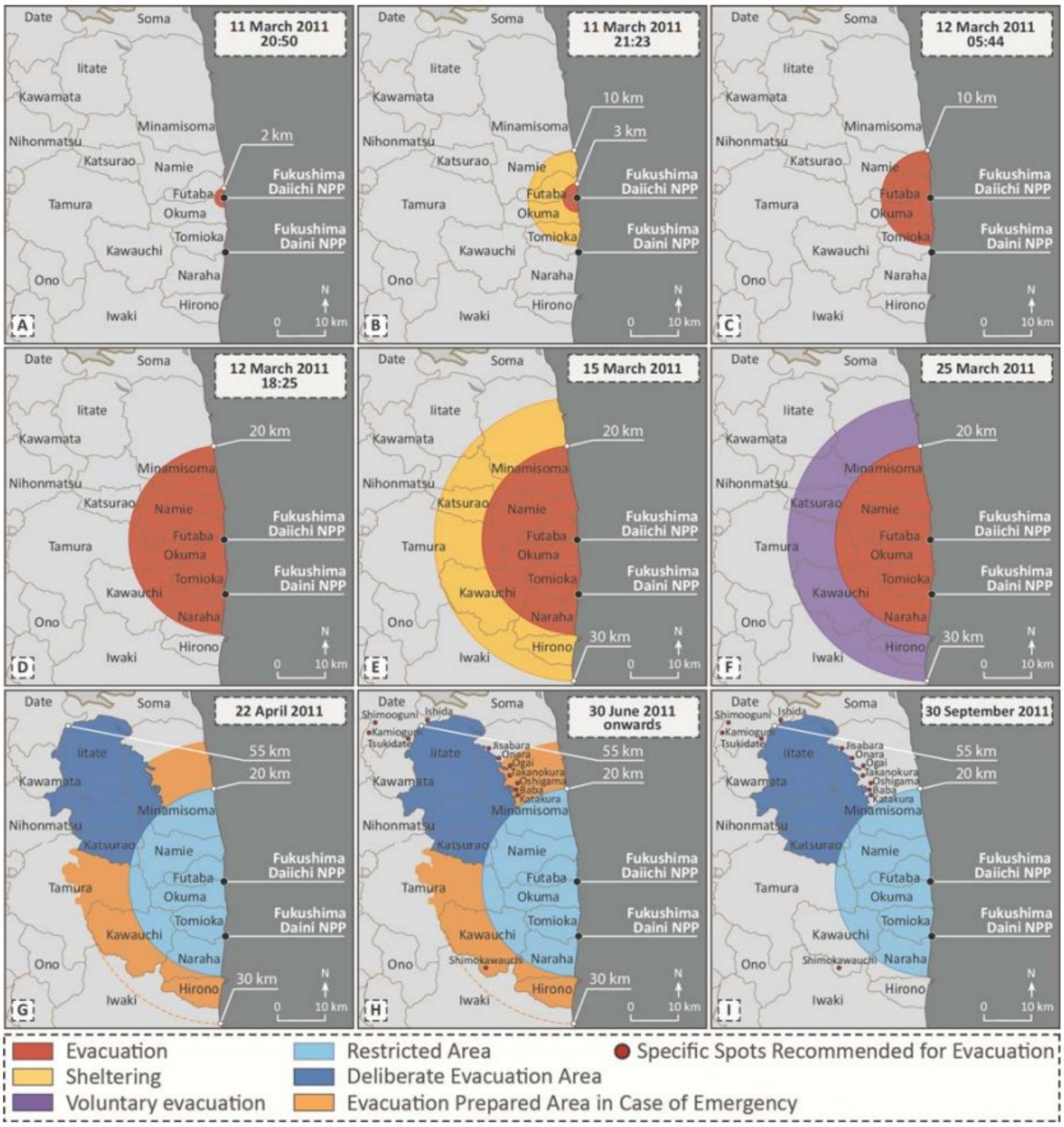

Figure 2.3. Ordered/recommended evacuation and sheltering zones for Fukushima Daiichi Nuclear Power Plant accident until September 30th, 2011. (IAEA, 2015, p.88)

When considering the examples of nuclear power plant accidents in history, it is concluded that all these nuclear power plants were constructed with different reactor types and technology, and these accidents have occurred due to various reasons, such as unforeseen human error or natural disasters. Furthermore, the implemented protective actions in response to these accidents reveal some insufficiencies. Even if one of the nuclear power plants has higher technology or is more qualified than another, nuclear risk will always be at stake. The French Atomic Energy Commission states that technical innovation cannot eliminate the risk of human errors or natural disasters in nuclear plant operations. Consequently, it is important to be prepared beforehand to protect the public and the environment and mitigate the potential consequences.

2.2 Regulatory Framework in the World

The capacity of ionizing radiation to cause damage to living organisms and the environment led to the world's concern to ensure the safe use of nuclear energy and protect living beings and the environment. Following the foundation of the International Commission on Radiological Protection (ICRP) in 1928, international actions in nuclear and radiation protection began in 1928 (Elbaradei et al., 1989). Then, the United Nations General Assembly established the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) in 1955 to evaluate the doses, impacts, and risks of ionizing radiation worldwide (Elbaradei et al., 1989). The work of these two bodies ensured the basis for the standards. Later, these standards were elaborated and improved by other international and regional organizations, such as the IAEA, International Labor Organization (ILO), World Health Organization (WHO), European Atomic Energy Community (EURATOM), and the OECD/NEA (Elbaradei et al., 1989). The IAEA was established as the world's "Atoms for Peace" organization in 1957 within the United Nations family. The agency works to support the peaceful use of nuclear technologies with its Member States and several partners worldwide (IAEA, 2014).

Under the terms of Article III of its Statue, the IAEA is authorized:

"To encourage and assist research on, and development and practical application of, atomic energy for peaceful uses throughout the world …."

"To establish or adopt … standards of safety for protection of health and minimization of danger to life and property … and to provide for the application of these standards" (The Satute of the IAEA, 1957).

The first safety standard of the IAEA, namely Safety Series No.1, Safe Handling of Radioisotopes, was published in 1958 and was upgraded throughout the years. The Safety Standards consist of three categories:

a. the Safety Fundamentals

b. the Safety Requirements

c. the Safety Guides.

They present an international consensus on what constitutes a high level of safety when implemented in an integrated manner. In general, the IAEA Safety Standards aim to control people's radiation exposure and the release of radioactive material to the environment, restrict the probability of events leading to a loss of control over any radiation source, and mitigate the consequences of such events (General Safety Requirements, 2016). The IAEA Safety Standards are prepared and reviewed with the involvement of five nuclear safety standards committees. These are:

- Emergency Preparedness and Response Standards Committee (EPReSC)
- Nuclear Safety Standards Committee (NUSSC)
- Radiation Safety Standards Committee (RASSC)
- Transport Safety Standards Committee (TRANSSC)
- Waste Safety Standards Committee
- The nominated experts from all IAEA Member States

The applicability of the IAEA Safety Standards throughout the entire lifetime of all existing and new nuclear facilities utilized for peaceful purposes makes them a reference for Member State’s national regulations in their nuclear facilities and activities so as Turkey (General Safety Requirements, 2016). In this regard, the IAEA is considered a focal point among other international and regional regulatory bodies to ensure the protection of people and the environment from the harmful effects of ionizing radiation (Elbaradei et al., 1989).

2.2.1.1 The IAEA Safety Standards – Preparedness and Response for a Nuclear or Radiological Emergency

The safety requirements for preparedness and response for a nuclear or radiological emergency (GS-R-2) were established in March 2002 by the IAEA's Board of Governors as a part of the IAEA safety standard, and they were issued in November 2002 with joint sponsorship by seven international organizations: the Food and Agriculture Organization of the United Nations (FAO), the IAEA, the ILO, the OECD/NEA, the Pan American Health Organization (PAHO), the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) and the WHO (General Safety Requirements, 2015). In general, they include an adequate level of preparedness and response requirements to mitigate the consequences of a nuclear or radiological emergency in case of such an emergency occurs (General Safety Requirements, 2015). This publication categorized the requirements into three sub-categories:

- General Requirements
- Functional Requirements
- Requirements for Infrastructure.

The governments are the responsible bodies for ensuring and maintaining these requirements. The General Requirements mention that an integrated and coordinated emergency management system for preparedness and response for nuclear or radiological emergencies shall be established. The roles and responsibilities shall be allocated among the regulatory body, operating, and response organizations. The hazard assessment shall be performed to ensure a basis for a graded approach in preparedness and response for a nuclear or radiological emergency, and protection strategies shall be developed based on the hazard assessed. The facilities with nuclear activities are categorized under five categories (Category I, Category II, Category III, Category IV, and Category V). Accordingly, nuclear power plants take part in Category I (General Safety Requirements, 2015).

The functional requirements consist of the critical functions for achieving the goals of emergency response. According to the functional requirements, nuclear or radiological emergencies shall be identified and notified to activate an emergency response. All nuclear or radiological emergency types are classified as:

- a general emergency
- site area emergency
- facility emergency
- alert
- other nuclear or radiological emergencies.

The emergency classification system aims to provide the prompt initiation of an effective response in recognition of the uncertainty of the available information. Mitigatory actions, such as preventing an escalation of an emergency, returning the facility to a safe and stable state, and mitigating the consequences of radioactive exposures, shall be taken. The off-site emergency planning zones (EPZs) and distances, precautionary action zone (PAZ), urgent protective action planning zone (UPAZ), extended planning distance (EPD), and ingestion and commodities planning distance (ICPD) shall be determined at the preparedness stage for effective protective actions. Instructions and warnings to the public on actions to be taken shall be provided (General Safety Requirements, 2015).

Requirements for Infrastructure include the infrastructural elements critical to fulfilling the functional requirements. Authorities, organizations, and emergency preparedness and response staffing shall be clearly established. The coordination among the operating organization and authorities at the local, regional and national level, and even international level, shall be provided, and emergency plans and procedures shall be established to respond to a nuclear or radiological emergency effectively (General Safety Requirements, 2015).

In the general requirement 5, it is clearly declared that the use of Operational Intervention Levels (OILs) is required as part of the protection strategies. The OILs are defined as the operational criteria allowing decision-makers to determine appropriate protective actions. Even if the safe design and high technology help reduce the risk of accidents, the risk of severe accidents has critical consequences on the living and non-living environment and future generations. Hence, it is essential to develop the appropriate emergency plans, with general objectives to reduce the risk or mitigate the accident's consequences and minimize the adverse health effects(Lauritzen et al., 1998). These general objectives are accomplished by interventions defined as countermeasures such as iodine prophylaxis, sheltering, evacuation, foodstuff restrictions, relocation, and access control in the IAEA safety standards series(Lauritzen et al., 1998). Within the scope of implementing the protective actions promptly, the OILs representing nine different countermeasures were developed. In the IAEA TECDOC-955, namely Generic Assessment Procedures for Determining Protective Actions During a Reactor Accident, the Operation Intervention Levels with the corresponding to the countermeasures, and their default values calculated in advance based on the characteristics of severe reactor accidents were declared in detail (See Table 2.2).

Table 2.2 *Operational Intervention Levels (OILs) (IAEA TECDOC-955,1997, p.228)*

OILs	**UNIT**	**DESCRIPTION**
OIL1	mSv/h	Evacuate based on ambient dose rates in plume
OIL2	mSv/h	Take thyroid blocking based on ambient dose rates in plume
OIL3	mSv/h	Evacuate based on ambient dose rates from deposition
OIL4	mSv/h	Relocate based on ambient dose rate from deposition
OIL5	uSv/h	Restrict food based on ambient dose rates from deposition
OIL6	kBq/m2	Restrict food or milk in area indicated based on deposition according to deposition levels of I-131
OIL7	kBq/m2	Restrict food or milk in area indicated based on deposition according to deposition levels of Cs-137
OIL8	kBq/kg	Restrict food or milk in area indicated based on deposition according to concentration of I-131
OIL9	kBq/kg	Restrict food or milk in area indicated based on deposition according to concentration of Cs-137

In Table 2.2, the units and descriptions belonging to the OILs are given. According to Procedure B1 in the IAEA TECDOC-955, the default threshold value for the OIL1 was calculated as 1 mSv/h, considering that the unsheltered person in the plume is exposed to ionizing radiation for 4 hours. Since this study only considers the evacuation as countermeasures based on the ambient dose rates in plume, the default threshold value of the OIL1 calculated by the IAEA is regarded as a reference.

The idea behind this publication is that good preparedness ahead of any emergency can improve the emergency response to a large extent. Consequently, it is an effective reference, including the requirements for preparedness and response for a nuclear or radiological emergency if implemented in a well-coordinated and integrated manner for the Member States (General Safety Requirements, 2015).

2.3 Postulated Initiating Events (PIEs) for NPPs

The IAEA defines 'Postulated Initiating Events' (PIEs) as "identified events that lead to anticipated operational occurrences or accident conditions." Krištof (n.d.) states that the PIEs are not practically accidents themselves; they are the events that initiate sequences. These sequences may lead to operational occurrences, design-basis accidents (i.e., core damage), or severe accidents depending on the successful operations of the various mitigating systems of the plants (Krištof, n.d.). Generally, a common set of PIEs is used for the deterministic safety analysis and the probabilistic safety analysis. The PIEs can be grouped into three which are:

- External hazards result from natural or man-made causes such as seismic events, aircraft crashes, etc.
- Internal hazards result from system failures within the operator's control but are not considered in the assessment process, such as fire.
- Equipment failures result from mechanical or electrical failures or loss of services.

Within the equipment failure group of the PIEs, the IAEA defines plenty of possible situations which may lead to a plant disturbance or core damage. Some examples of the PIEs by equipment failure are given below:

- Increase/decrease in heat removal by the secondary system (i.e., steam line break event)
- Anomalies in reactivity and power distribution (i.e., ejection of a control rod assembly)
- Increase/decrease in coolant inventory (i.e., loss-of-coolant accident (LOCA))
- Radioactive release from a subsystem etc. (Jacquemain et al., 2015).

As aforementioned, the PIEs may end up with core damage. In the Tecdoc-955 by the IAEA, five different core damage are identified for the light water reactors: PWR and BWR. One of them is a core melt release assuming the entire core has melted.

The PIE used in this study is a large break loss-of-coolant accident (LBLOCA) along with a station blackout (SBO) as a hypothetical accident scenario in one of the reactor units of the Akkuyu Nuclear Power Plant. It is assumed that Emergency Core Cooling System is unavailable, resulting in rapid depressurization in the core. These sequenced events lead to the core meltdown and fission product release into the containment via the break. Since all filtration and ventilation systems are dysfunctional due to SBO, the fission products start to escape from the containment via the vent stack.

2.4 Atmospheric Dispersion Models

Atmospheric dispersion modeling is the mathematical expression of how air pollutants disperse through the atmosphere. Dispersion models include algorithms to estimate the downwind concentration of air pollutants or chemicals. They are also used to estimate future air quality under specific scenarios. Dispersion models are important to governmental agencies, public safety responders, and emergency managers for emergency planning to protect and manage air quality (EPA, 2022).

Leelössy et al. (2018) summarize the historical development of atmospheric dispersion models as follows:

- Atmospheric dispersion research date back to the early 1920s.
- Early numerical models were started to develop with the aim of nuclear and chemical defense during the ongoing cold war.
- The Clean Air Act (1963) led to transform the aim of developing numerical models for atmospheric dispersion from chemical defense to emission regulations. The developments in this area mainly focused on local-scale effects of stack releases using the Gaussian approach until the late 1970s.
- By the early 1980s, new environmental challenges arose, leading to a paradigm shift in dispersion modeling. The accidents in Seveso (1978) and Bhopal (1984) raised awareness about not only continuous air pollution but also a single release can lead to catastrophic consequences.
- On the other side, the acid rains started to pose a serious problem, forcing regulators and model developers to extend the scale of the simulations to the continental level. Eulerian and Lagrangian models enabled the scale shift. The Chernobyl accident in 1986 led to the development of continental-scale decision support models to be boosted. There was no prognostic modeling in Chernobyl because of the secrecy in the first days of the accident.
- The period between Chernobyl and the end of the century was considered a development area for dispersion models. The first large-scale nuclear disaster with operational atmospheric dispersion forecasts for emergency response was the Fukushima Daiichi nuclear disaster. (2011).

Many dispersion models, which vary depending on the numerical approaches used to develop the model, different physical assumptions, and implementation, are available in the literature. However, not all of them are associated with radionuclide release (IAEA TECDOC-379, 1986). Several numerical approaches are used in developing atmospheric dispersion models for radionuclides, mainly Gaussian, Eulerian, and Lagrangian Approaches.

The term “Gaussian” means the statistical concept in which a group of arranged values follows a bell-shaped curve distribution. Djangmah (2013) states Gaussian type models supposing that the pollutant disperses in accordance with the normal statistical distribution as one of the most common dispersion models used in atmospheric dispersion modeling. According to Gaussian-type models, the pollutant concentration is at maximum at the point of release, and then it decreases in both lateral and vertical directions following the normal distribution (Djangmah, 2013). Their fast runtime and small input data requirement can be regarded as advantages; however, their accuracy is very limited over the long-range spatial distance. Their accuracy is also limited in complex conditions such as orography, and wind shear (Leelőssy et al., 2018), since they assume that the terrain is relatively flat, the wind direction and speed are constant, and net downwind diffusion is negligible (Djangmah, 2013).

The Eulerian model is a set of second-order partial differential equations with the independent variables of space (x,y,z) and time (t) mathematically. Solving this equation provides the Spatio-temporal variation of the radionuclides concentrations (Leelőssy et al., 2018). The Eulerian models are based on a fixed three-dimensional cartesian grid as a frame of reference, and they assume that emissions are spread evenly throughout each model grid cell (Djangmah, 2013).

A Lagrangian dispersion model is a set of first-order stochastic ordinary differential equations describing many particles' motion(Leelőssy et al., 2018). The frame of reference of the models follows the prevailing vector of atmospheric motion, which helps differentiate them from the Eulerian models. After several nuclear accidents, the Lagrangian approach ensures the core of global-scale atmospheric dispersion simulations. Among several others, three software, namely the HYSPLIT (1980), NAME (1986), and FLEXPART (1998), are the internationally most widely used, and these models still provide the basis of global-scale nuclear dispersion modeling (Leelőssy et al., 2018).

2.4.1 The Hybrid Single-Particle Lagrangian Integrated Trajectory (HySPLIT) Model

The atmospheric dispersion models simulate the dispersion process of radionuclides released into the atmosphere in nuclear accidents with different ranges by using divergent mathematical methods. The radionuclides are transported in the atmosphere with the mean wind and dispersed by turbulence. In addition, they are deposited on the ground either through precipitation, namely 'wet deposition,' or/and sticking to the surface, called 'dry deposition.'

The HySPLIT model was developed and maintained by the United States National Oceanic and Atmospheric Administration-Air Resources Laboratory (NOAA-ARL) (Stein et al., 2015). Stein et al. (2015) define HySPLIT as a complete system since it can compute both air parcel trajectories and complex transport, dispersion, chemical transformation, and deposition simulations. The model has a hybrid approach between the Lagrangian approach, which uses a moving frame of reference for the calculations, and the Eulerian approach, which uses a fixed three-dimensional grid as a frame of reference, to compute the transport, dispersion, and deposition of pollutants, radionuclides, smoke, etc. (Stein et al., 2015). The model can simulate the sources that release pollutant puffs or many particles over the duration of the release. Since the model is incorporated with a hybrid approach, it can compute the particle dispersion in the vertical direction while puff dispersion in the horizontal direction. Regardless of which approach is used, the model requires the gridded meteorological data with regular time intervals for the computation of stability and mixing coefficients (Draxler & Hess, n.d.; Ünver, 2003). Additionally, the model has the option of computing wet and dry deposition, radioactive decay, resuspension, etc. (Pirhalla, 2021).

Besides the operational use within NOAA, the HySPLIT model is one of the most widely used atmospheric transport and dispersion models in the atmospheric sciences community since the model provides a higher dispersion accuracy of the vertical particle treatment with the combination of the spatial resolution benefits of the horizontal puff splitting (Ünver, 2003). In addition, the HySPLIT is fast and free software providing dispersion simulations with high accuracy. For these reasons, all model runs for atmospheric dispersion modeling of Cs-137 and I-131 in this study were made in HySPLIT 3D particle horizontal and vertical mode.

2.4.2 Source Term

Source term is the key factor for the radiological assessment and accidental consequence analysis. The US NRC (2021) briefly defines it as "types and amounts of radioactive material released to the environment following an accident." There are plenty of factors characterizing the source term such as the accident scenario, the type of reactor unit, core inventory determined by the thermal power of the reactor, the fuel burnup, chemical/physical form of the released materials, release fraction, release duration, release height, etc. Any changes in the factors would lead to different source term estimations (Nalbandyan et al., 2012). In the report of the US NRC, namely NUREG-1150 (1990), the risk of five different reactors in the US was assessed, and the source terms were characterized considering the fractions of the core inventory that are released to the environment, duration, and elevation of release (Ünver, 2003). According to the report of the US NRC, namely NUREG-1465, radioactive species considered in design basis analysis in the reactor inventory are collected in eight radionuclide groups and presented in Table 2.3.

Table 2.3 *Radionuclide Groups (NUREG-1465, 1995, p.10)*

Group	Title	Elements in Group
1	Noble gases	Xe, Kr
2	Halogens	I, Br
3	Alkali Metals	Cs, Rb
4	Tellurium group	Te, Sb, Se
5	Barium, strontium	Ba, Sr
6	Noble metals	Ru, Rh, Pd, Mo, Tc, Co
7	Lanthanides	La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y, Cm, Am
8	Cerium group	Ce, Pu, Np

2.4.3 Dose Conversion Factor

The ICRP developed the concept of 'effective dose' (E), which is a risk-adjusted dosimetric quantity for radiation protection enabling the comparison of planned or received doses with dose limits, and reference levels (Annals of the ICRP, 2018). Assessment of radiation risks for individuals provides the implementation of the limitation principles against radiation exposure (Menzel & Harrison, 2012). The ICRP (2018) has introduced effective dose as the principal radiological protection quantity to be used for setting and controlling dose limits in the regulatory context and for the practical implementation of the optimization principle (Annals of the ICRP, 2018). The effective dose coefficients tabulated in various reports of different national organizations of countries generally apply to a "reference person" of the stated age.

In the ICRP Publication 103 (2007), "reference person" is defined as "An idealized person for whom the organ or tissue equivalent doses are calculated by averaging the corresponding doses of the Reference Male and Reference Female." The equivalent doses of the Reference Person are used to calculate the effective dose by multiplying these doses by the corresponding tissue weighting factors. All effective dose rate coefficients presented in this report are sex-averaged and derived using mathematical hermaphrodite phantoms for newborns, children ages 1, 5, 10, and 15 years, and adults. Averaging of dose rate coefficients for males and females of a given age yields a dose rate coefficient for a "reference person" of that age. This report tabulates age-specific, reference person effective dose rate coefficients for external exposure to photons and electrons emitted by radionuclides distributed in air, water, and soil. The dose rate coefficients are intended for use in the calculation of age-specific effective doses from external exposure to radionuclides in the environment. This research considers the calculated dose conversion factors from the Federal Guidance Report No.15 by the US EPA. Dose rate coefficients are provided in this report for the following exposure pathways: submersion in a contaminated atmospheric cloud (air submersion), exposure to contamination on or below the ground surface (ground exposure), and immersion in contaminated water (water immersion). For each exposure pathway, dose rate coefficients are provided for 1,252 radionuclides (Federal Guidance Report No. 15, 2019).

2.4.4 Radiation Exposure Pathwhays

According to the IAEA safety standards, there are generic criteria for determining threshold values for protective or response actions in an emergency. These thresholds depend on the exposure pathways of ionizing radionuclides (General Safety Guide No. GSG-8, 2018). The impact assessment of ionizing radionuclides on humans and the estimation of dose values differ in accordance with exposure pathways (General Safety Guide No. GSG-8, 2018).

The exposure pathways are illustrated in Figure 2.4. There are internal and external routes that people can be exposed to radiation (Bilgiç & Gündüz, 2020). Internal exposure can occur via inhalation of radioactive material from passing plume, inhalation of radioactive material from following resuspension of the ground deposit, and ingestion of the contaminated foodstuffs by radioactive material. External exposure can occur via radioactive material in the passing plume, namely cloud-shine, radioactive material deposited on the ground, called ground-shine, and radioactive material deposited on skin and clothing (Miller, 2015). There can be many pathways by which people are exposed to nuclear radiation. (Bilgiç & Gündüz, 2020). This study considers only the cloud-shine pathway for dose assessment released from a hypothetical nuclear power plant accident in Akkuyu-NPP.

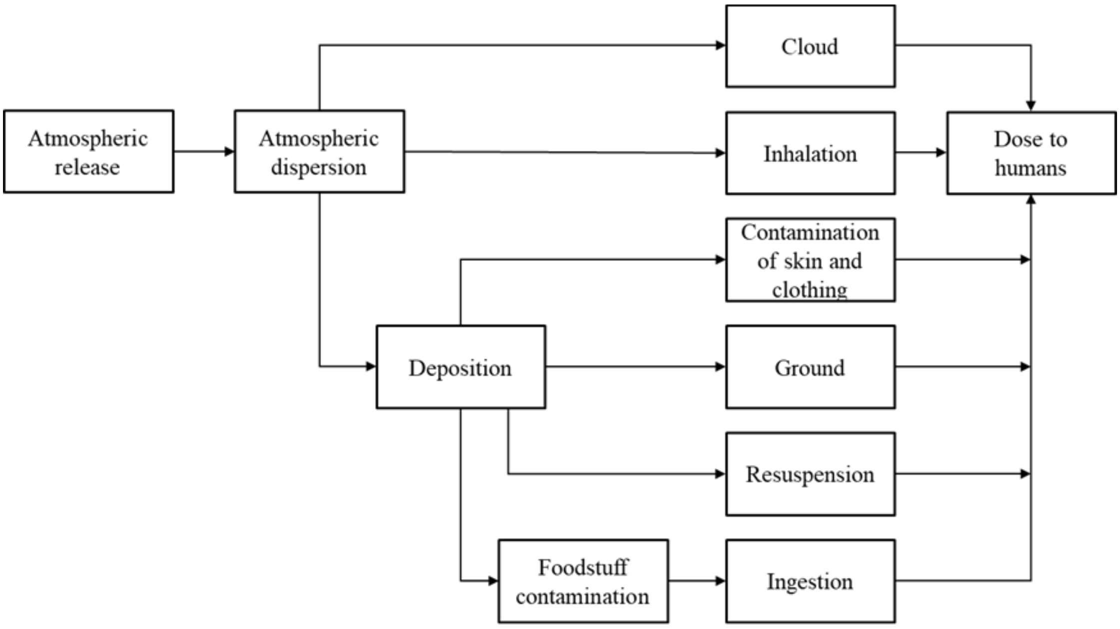

Figure 2.4. Exposure pathways of ionizing radionuclides to humans following an atmospheric release (Miller, 2015, p.166)

2.4.5 Meteorological Data

One of the most important factors in modeling atmospheric dispersion of radionuclides is the accuracy and spatial resolution of the meteorological input data since dispersion calculations depend directly on the meteorological data (Almeshari, 2009). Many meteorological parameters affect the atmospheric dispersion of radionuclides, and the most important of them are wind speed, wind direction, boundary layer height, and atmospheric stability, which is called a Pasquill stability criterion (Hall & Spanton, 1999). These four parameters are assumed to be sufficient for measuring air concentrations of I-131 and Cs-137. While wind speed and direction are fetched directly from prevailing around the Akkuyu Nuclear Power Plant reactor site, the boundary layer height and stability criteria are derived from the time of day, solar radiation, and cloud cover (Hall & Spanton, 1999).

Different scenarios were defined to observe better the potentially risky areas resulting from the predefined hypothetical nuclear power plant accident in Akkuyu

Nuclear Power Plant. Therefore, local and regional meteorological conditions of Akkuyu Nuclear Power Plant surrounding in 2021 were examined and simulation periods were determined to represent different meteorological conditions which are low, average, and extreme. The meteorological data input for all simulations including sensitivity runs, was also provided from ARL (Air Resource Laboratory) Archive.

The ARL archive contains several meteorological datasets available at various temporal and spatial resolutions, which are already converted into a HySPLIT-compatible format. The 3-hourly archive data with 1° x 1° grid resolution come from the Global Data Assimilation System (GDAS). The GDAS is one of the operational systems of the National Weather Service's National Centers for Environmental Prediction (NCEP), and it is run 4 times a day, at 00, 06, 12, and 18 UTC. The upper level GDAS data are output on the following 23 pressure surfaces: 1000, 975, 950, 925, 900, 850, 800, 750, 700, 650, 600, 550, 500, 450, 400, 350, 300, 250, 200, 150, 100, 50, and 20 hPa. The meteorological data fields in the GDAS archive contain temperature at the surface in °K, relative humidity in %, vertical pressure velocity in hPa/s, geopotential height in gpm*, u and v component of wind with respect to the grid in m/s, etc. However, GDAS data with 1° x 1° grid resolution does not include the sigma coordinate system.

2.5 The Health Effects of Cs-137 and I-131

Understanding the possible health effects and life losses in a radioactive emergency is essential to help emergency managers and decision-makers determine how the effects can be mitigated and which countermeasures should be implemented (Harris, 2014). The effects of ionizing radiation on the human body depend on exposure pathways, internal or external, and they vary in accordance with the whole-body exposure or local exposure, the amount of radiation, and the duration of exposure (Ministry of Environment, Japan, 2019.).

Radiation effects are separated into two types: i) deterministic effects and ii) stochastic effects. 'Deterministic effects' are defined as damage to tissues and organs, and they mostly occur immediately (Bundesamt für Strahlenschutz, 2020). Deterministic effects have the threshold dose, which means that the effects only occur when the threshold dose has been exceeded. The exposure dose below the threshold level causes no effects. The severity of deterministic effects is directly proportional to the exposure dose. In other words, the severity of the effects increases when the exposure dose increases (SCENIHR, 2012). Radiation-induced skin burns (skin erythema), acute radiation syndrome, hair loss, cataracts, temporary or permanent sterility, and radiation sickness are some examples of deterministic effects (Bundesamt für Strahlenschutz, 2020).

'Stochastic effects' are the probabilistic effects that occur only with a certain probability and are referred to as changes in the genetic material of cells due to radiation exposure. The stochastic effects assume that there is no threshold dose to be affected. Although the probability of damage depends on the dose, the severity of damage is not affected by the dose. Cancer, leukemia, hereditary defects, etc., are some instances of stochastic effects of radiation exposure (Bundesamt für Strahlenschutz, 2020).

Cs-137 is one of the most common fission products in nuclear processes, nuclear weapon tests, or major nuclear accidents, with a physical half-life of 30 years and a biological half-life of 70 days (US NRC, n.d.). A physical half-life of the radioactive elements is defined as the amount of time needed for half of the material to decay. According to the US NRC, a biological half-life is the required time for half of the material to be expelled from the body. Cs-137 has been regarded as a dangerous fission product since its 30 years half-life, combining high-energy radioactivity and chemical reactivity. Its half-life is long enough to make objects and regions contaminated by Cs-137 dangerous for humans for generations (Wessells, 2012). While external exposure to large amounts of Cs-137 can cause burns, acute radiation sickness, and even death, internal exposure leads Cs-137 to be distributed through the whole body, especially the soft tissues, and increases the cancer risk (CDC, 2018).

I-131 is the product of nuclear fission processes with a physical half-life of 8 days and a biological half-life of 80 days (NRC, n.d.). External exposure to large amounts of I-131 leads the eyes and skin to burn. Since the thyroid gland uses iodine to produce thyroid hormones and cannot distinguish between radioactive iodine and non-radioactive iodine, internal exposure to large amounts of I-131 affects the thyroid gland (CDC, 2018). When the I-131 is once received inside the body, it is absorbed by the thyroid gland to produce thyroid hormones, increasing the risk for thyroid cancer in the long term (CDC, 2018).

2.6 Evacuation Planning in case of Nuclear Power Plant Accidents

Evacuation is the process of moving the population from a dangerous place to a safe location and is regarded as the most effective countermeasure. Evacuation protects people from natural or man-made hazards, including nuclear power plant emergencies, minimizes the risk of potential casualties and injuries, and requires a proper plan. (Southworth, 1991). IAEA Safety standards (2015) require that the member states maintain an adequate level of planning and preparedness, including countermeasures ensuring the safety of people in a nuclear emergency. Evacuation planning is considered a procedure indicating the evacuation process and has been imposed on the nuclear industry as the main component of emergency planning since the early 1980s (Ayfadopoulou et al., 2012). Evacuation plans may be prepared in every phase of the disaster cycle: Mitigation, Preparedness, Response, and Recovery; however, they should be ideally generated during the emergency preparation step to protect the live and non-live environment.

The evacuation planning is hard to be executed since it is a comprehensive work involving many aspects. The evacuation process of the most known nuclear disasters in history (Three Mile Island, Chernobyl, and Fukushima) reveals several insufficiencies (Malešič et al., 2014). In the Three Mile Island Nuclear Power Plant accident, some residents evacuated the area voluntarily with private cars, owing to insufficient information sharing, which caused traffic disruption (Smith and Fisher, 1981). In the Chernobyl Nuclear Power Plant accident, the accurate information provided to the residents on the accident and radiation was insufficient (Likhtarev et al., 1994), and many children were evacuated to the summer camp sites being separated from their families (Soffer et al., 2008). The lack of advance planning and inadequate appropriate transport and care for the ill caused tragic deaths of hospitalized patients during evacuation in the Fukushima Daiichi Nuclear Power Plant Accident (Tanigawa et al., 2012). Hence, it is crucial to consider various possibilities and the related feasibilities during the evacuation process.

Moynihan et al. (2016) explain that evacuation plans can be implemented considering the historical data or simulation base 'what-if' scenarios. A historical data-based evacuation plan requires a record, including the experience of such a disaster; however, a simulation-based evacuation plan provides a 'what-if' analysis and can be implemented in all places vulnerable to a certain hazard. The simulation-based evacuation planning has several advantages; these are:

- providing to observe the total operational flow with an opportunity for 'what-if' analysis
- providing to analyze any impacts under various conditions
- providing to evaluate the alternative decisions to optimize the budget without disrupting existing operations or incurring unnecessary evacuation costs.

Ayfadopoulou et al. (2012) consider evacuation planning to be executed in a systematic framework since it is influenced by many operational and management facets and develops a summary of the evacuation planning steps (See Figure 2.5.). The first step requires the identification of the region to be evacuated. Hazard mapping is a common strategy contributing to detecting evacuation zones and prioritizing them according to the vulnerability to the hazard. The second step includes the demand estimation over the evacuation area and the determination of the safe zones and possible exit points considering their capacity, accessibility, and proximity according to the evacuation demand. The second step provides for the development of the third step, which is the traffic assignment computing the optimal routing of evacuation to the pre-defined safe zones (i.e., evacuation routing). This step requires a detailed analysis of the roadway characteristics and background traffic information to be achieved. The fourth step corresponds to the evacuation time estimation (ETE), which is the elapsed time for the traffic originating within the evacuation zone to the safe zone. The ETE is based on scenarios with different meteorological conditions and recalculated at different alterations. At the end of the evacuation planning steps, the ETEs are evaluated to determine whether the calculated time is adequate to clear the evacuation zone or not.

Consequently, evacuation planning is a complete process associated with optimizing evacuation routes and calculating the required evacuation time through several iterations (Goldblatt, 2004). In addition, reasoned evacuation planning helps emergency planners to decide whether to prevent unnecessary evacuation or to evacuate the area soon enough. In this way, the operational cost of evacuation is minimized, and any fatalities are avoided (Lindell and Prater, 2007)

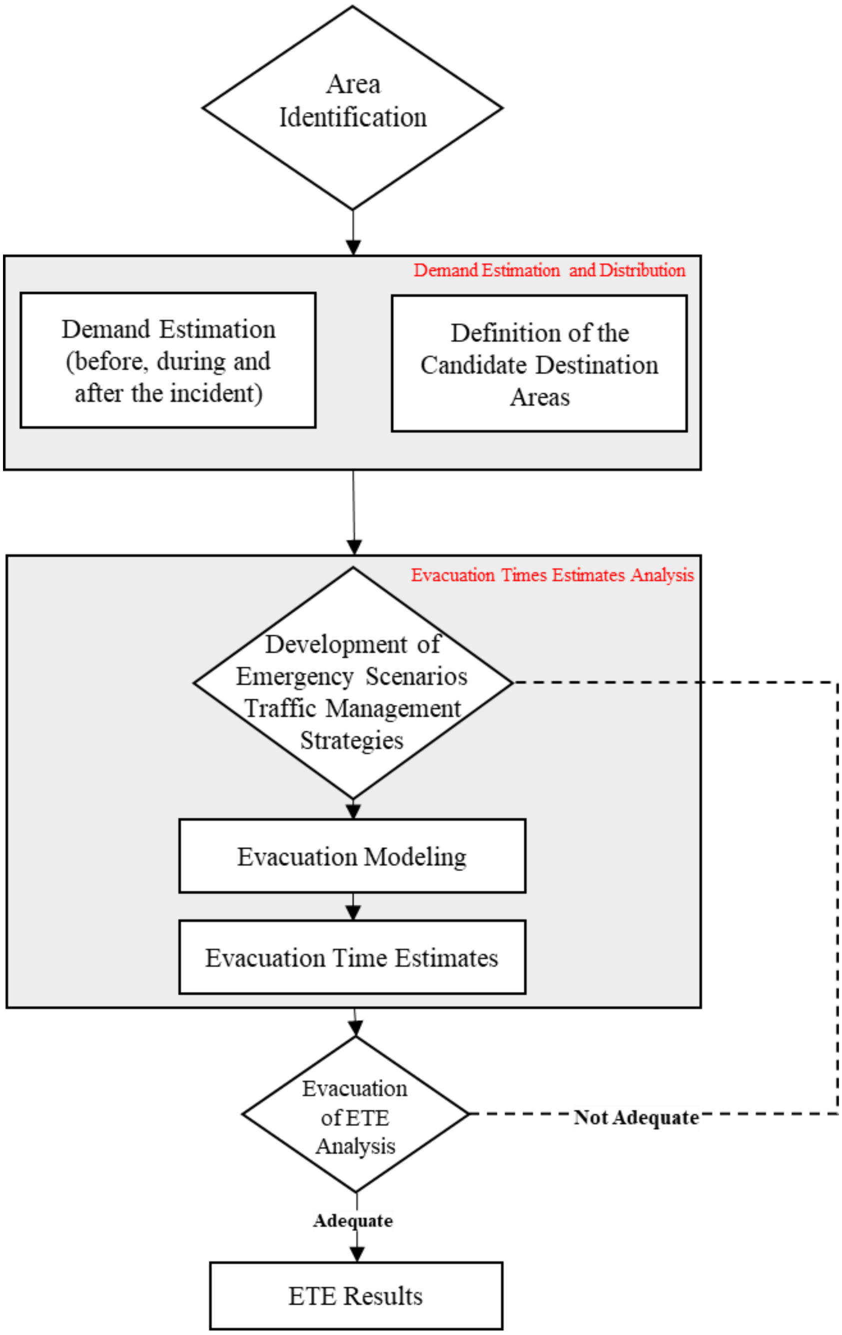

Figure 2.5. Evacuation planning steps (Ayfadopoulou et al., 2012, p.2)

2.6.1 Hazard Mapping

Hazard, disaster, and risk are different concepts. In UNDRR Global Assessment Report (2015), a hazard is defined as an event with the potential to cause injury, loss of life, or damage to the environment; however, hazards may or may not become a disaster depending on the choices or behaviors of humans. On the other hand, disaster risk is regarded as the combination of hazard, exposure, and vulnerability, called the risk function (See Figure 2.6.) (UNDRR Global Assessment Report, 2015).

Figure 2.6. Risk function (UNDRR, n.d.)

Sagara et al. (n.d.) explain that understanding hazards via quantitative estimation of potential damage is essential since it uniforms the appropriate strategies for countermeasures to be taken in disaster risk management. Hazard mapping is considered the crucial step in disaster risk management and emergency preparedness since it contributes to hazard assessment. It is developed to illustrate areas affected by or vulnerable to a particular hazard. Thus, hazard mapping estimates the hazard levels and mitigates the disaster by formulating disaster management policies (Sagara et al., n.d.).

In the literature on disaster risk management, two main approaches are defined for hazard mapping, depending on the type of data analyzed, which are the same approaches defined for evacuation planning. The first approach evaluates the accumulation of events in which the historical records. The second approach estimates the range of influence via simulations based on "what-if" scenarios in certain conditions (JICA, n.d.). In all cases, the main objective of hazard mapping is to analyze the spatial distribution of hazards. It includes hazard zonation, which is the division of the land surface into areas by ranking according to the actual or potential hazard, and hazard hotspots, which identify a relatively high probability of loss from the hazard (Atkinson et al., 2012). Nevertheless, hazard assessment via hazard mapping should not depend solely on historical records since the maximum-possible hazard levels that may occur in the feature may not be included in historical records, or the records may not be available (Sagara et al. (n.d.)). On the other hand, simulation-based hazard mapping can be implemented in places vulnerable to a certain hazard without any experienced disasters.

Consequently, hazard mapping is critical since it provides the base for disaster risk management policies. It promotes risk awareness and designing countermeasure strategies (i.e., evacuation, shelter-in-place). Therefore, the local conditions of the areas vulnerable to a certain hazard should be regarded in the hazard mapping process to provide a more precise hazard assessment. Additionally, the hazard maps should be revised periodically considering the latest findings, changing conditions, and recently experienced disasters (Sagara et al. (n.d.)).

2.6.2 Evacuation Zoning

The evacuation process requires disaster responders to identify the locations to be evacuated, the evacuation demand, evacuation routing, and ETEs. However, Hsu (2013) states that the operational context of evacuation can be significantly characterized by the time dependency of disaster characteristics, traffic demand patterns, and network supply conditions. In other words, evacuation operations are highly dependent on dynamic factors that may continuously evolve during the evacuation process. For instance, varying wind direction and wind speed during the nuclear fallout may directly affect the further steps of evacuation planning. Therefore, pre-defined EPZs (See in Section 2.3.) may not correspond to the dynamic changes reducing the performance of evacuation operations. Hence, hazard mapping enables evacuation operations to proceed more efficiently by specifying the locations vulnerable to a certain level of disaster impact (Hsu, 2013). In 2019, Federal Emergency Management Agency (FEMA) published the Planning Considerations: Evacuation and Shelter-in-Place guidance to provide unique considerations in developing evacuation plans. FEMA (2019), in the guidance, presents evacuation zoning as one of the key concepts to increasing the efficiency of an evacuation.

Evacuation zones allow emergency responders to identify the most vulnerable areas and people and help them prepare efficient emergency preparedness plans. (FEMA, 2019) Thus, disaster responders focus on the specific areas during the evacuation process, which helps them estimate the evacuation demand and supply, identify the safe zones, and assign the evacuation routing efficiently. Schaefer (2019) states that well-estimated evacuation demand and supply provide the optimal traffic flow and resource allocation during the evacuation.

Additionally, the further step of evacuation zoning is prioritizing the evacuation zones based on the impact level of the disaster, which ensures increasing traffic efficiency and decreasing overall evacuation clearance time (Schaefer, 2019)., Prioritized evacuation zones prevent evacuating large areas without the threat of hazards and help reduce the chance of clogged highways. Hence, the evacuation zone identification and prioritization of the zones are the initial steps of evacuation planning and significant guides to emergency responders due to providing a base for further steps of the evacuation planning framework.

2.6.3 Evacuation Demand Estimation

Evacuation demand estimation corresponds to the number of people in the defined evacuation zones (Smith, 2021). The prediction of evacuation demand is a significant step since it directly affects the performance of evacuation routing. Comprehensive evacuation demand estimation requires identifying the temporal and spatial distribution of the population within the evacuation zones (Moynihan et al., 2016). Nevertheless, demand profiling contributes to identifying transport needs and evacuation routing. Smith (2021) declares in the report “Criteria for Development of ETE Studies” that the demand profile within the evacuation zones is separated into four groups: permanent residents, transient population, transit-dependent permanent residents, and special facility residents and schools. Permanent residents consist of the people living in the region, while the transient population includes people temporarily in the region, such as tourists, employees, shoppers, etc. Transit-dependent permanent residents are defined as those who do not have access to a vehicle. Special facility residents consist of those in nursing homes, hospitals, prisons, etc., while schools include all private and public educational facilities. The demographic data acquisition regarding the demand profile requires detailed research. Therefore, this research estimates the evacuation demand considering the permanent residents within the identified evacuation zones. The further steps of evacuation planning are beyond the scope of this research.

2.6.4 Identification of Safe Zones

The main objective of evacuation planning is displacing people from a dangerous place to a safer place in an emergency. Saadatseresht (2008) states that it is important to identify the safe zones considering their capacities and the distance of the evacuees to the safe zones, before assigning and optimizing the evacuation routes. Generally, available green, open, and vacant lands outside the hazard zones are assigned as safe zones; however, the possible expanding range of the hazard zone should also be considered in identifying the safe zones. Besides, these lands should have enough space for evacuees and include basic living requirements (clean water, toilet, electricity, etc.) to be considered safe zones. Additionally, the appropriate places can be identified using satellite image processing and fieldwork and prepared to be used as safe zone subsequently (Saadatseresht, 2008). Identifying the distribution of the evacuees into the safe zones, in other words deciding where and from which road each evacuee should go, is one of the significant challenges of evacuation planning since the objectives to be considered may conflict. Therefore, integrating the GIS before, during, and after an emergency may be beneficial since identifying safe zones requires the spatial component mostly.

2.6.5 Evacuation Routing

Evacuation operations require a comprehensive analysis due to involving the substantial logistic complexities. Evacuation routing aims to distribute evacuees on routes from the evacuation zones to designated safe zones in an optimum way (Shekhar et al., 2012). Although evacuation demand estimation and safe zone identification within the scope of evacuation zoning determined by hazard mapping have significant contributions to optimum evacuation routing, several factors and constraints must be considered in this process (Han et al., 2006). One of the main factors affecting evacuation routing is identifying the roadway capacity within the evacuation zones. Smith (2021) defines roadway capacity as the percentage factor displaying the maximum rate at which vehicles can be anticipated to pass through a roadway section under certain conditions, such as prevailing roadway, traffic, control points, and adverse weather in a given time. Since the roadway capacity directly affects the next step of evacuation planning, that is, evacuation egress time estimation, it must be analyzed in detail by categorizing it according to the functions and obtaining the characteristics. Apart from the roadway characteristics (number of lanes, lane-width, interchanges, speed limits, etc.), disaster characteristics, background traffic, person-vehicle ratios, and behavior of evacuees affect evacuation routing.

Han et al. (2006) state that the major constraints in evacuation routing are limited exit routes and insufficient roadway capacities to cope with a large-scale evacuation. City transportation networks are generally not designed to deal with the sudden evacuation of numerous people (Shahabi, 2012). Design deficiencies of transportation networks lead to not corresponding to the high traffic demand within a short period. (Cova, 2002). Hence, insufficient capacity and design deficiencies of the existing roadway network may cause eventual bottlenecks susceptible to potential accidents and evacuation delays subsequently (Campos, 2012). Consequently, it is important to focus on developing optimized evacuation routing before, during, and after the emergency considering potential constraints and problems to maximize the utility of the existing transportation network and minimize the evacuation time egress (Han et al., 2006).

2.6.6 Evacuation Time Estimation (ETE)

Evacuation should be implemented fastest and most efficiently to minimize exposure to potential hazards. Evacuation Time Estimation (ETE) is a significant issue in measuring evacuation efficiency (Chen et al., 2019). Wolshon et al. (2020) denote ETEs are the time analysis required to evacuate hazard zones. The basic methodology of ETEs is to identify whether the evacuation demand is higher than the offered traffic capacity. Suppose the evacuation demand is lower than the roadway capacity. In that case, the evacuation time is equal to the time from when the first evacuee begins evacuating to the last evacuee leaving the evacuation zone. However, if the evacuation demands are higher than the existing roadway capacity, ETE should consider the delay due to demand surplus (Urbanik, 2000).

Urbanik (2000) reports that developing ETEs involves various considerations with several assumptions. ETEs should consider the adverse weather conditions, the possibility of changing the disaster profile, and the trip generation time, which is the elapsed time between the warning receipt and the evacuees' departure. Additionally, ETEs should assume (i) driver behavior, (ii) evacuation time for transit-dependent populations and special facility populations, and (iii) the time required for confirmation of the warning response by the population situated in the evacuation zones. While developing a single ETE is insufficient in an emergency regarding the wide range of considerations in the developing process, developing ETEs considering each possibility is impractical. Hence, developing a range of ETEs is appropriate and reasonable (Urbanik, 2000)

ETEs are beneficial due to providing essential information if traffic management actions that would decrease the evacuation times or not and guide effective traffic management plans in an emergency. Additionally, the well-estimated evacuation times, considering the variations in the developing process, minimize people's exposure to a certain hazard.

CHAPTER 3

NUCLEAR POWER IN TURKEY

The purpose of this chapter is to summarize the history of the nuclear power projects in Turkey and the main characteristics of the first NPP, the Akkuyu-NPP in Mersin, Turkey, to lay a foundation for the upcoming evacuation planning steps in the methodology.

3.1 The History of Nuclear Energy in Turkey

According to the Country Nuclear Power Profile (CNPP) project, initiated by International Atomic Energy Agency (IAEA), the background information on the status and development of nuclear power programs has been compiled since the 1990s. Turkey's nuclear power profile is reported as one of the member states. This report underlines the increasing energy demand in Turkey in parallel with its economic development over the past decades (IAEA-CNPP, 2021). The highlights of this report can be summarized as follows:

- Although Turkey has almost all conventional resources, these are inadequate to meet this dramatic growth in energy demand. This insufficiency makes Turkey dependent on other countries in terms of energy supply. Turkey has intensified efforts at further diversification in primary energy sources due to the substantial growth of energy demand and policies aimed at decreasing foreign-source dependency in the energy sector. As a result, it was decided that nuclear energy is the best way to achieve diversification and sufficiency of energy supply in Turkey (IAEA-CNPP, 2021).
- Turkey has made various attempts to build an NPP. From 1965 to 1974, the projects to build nuclear power plants were canceled due to site selection

problems. In 1974, the Akkuyu field in Mersin province was decided as the most suitable place.

- After Atomic Energy Commission granted a site license for Akkuyu in 1976, contract negotiations were started with the ASEA-ATOM and STAL-LAVAL companies. However, the project was canceled due to the withdrawal of a loan guarantee (IAEA-CNPP, 2021).
- In the 1980s, Akkuyu-NPP Project was restarted; however, the 1986 Chernobyl accident stopped/canceled all NPP projects worldwide.
- During the 1990s, although the Supreme Council for Science and Technology declared that electricity generation from nuclear energy was the third-highest priority for Turkey (IAEA-CNPP, 2021), the Turkish government had to postpone the Akkuyu-NPP due to financial problems, changes in governmental authorities, and the occurrence of two earthquakes, one of which is only 150 km away from Akkuyu (Akcay, 2009).
- In 2010, the Akkuyu Nuclear Power Plant started to be constructed after the agreement between Turkey and the Russian Federation on a build-own-operate model.
- In 2013, an agreement was signed with Japan to construct the second NPP in Turkey at Abalı, Sinop (Akcay, 2009).

According to the Russian Federation's agreement, there will be four units, including WWER-1200 type reactors, with 1200 MW(e) capacity for each in Akkuyu until 2026. Furthermore, there will be a total installed capacity of 4800 MW(e), and each reactor's lifetime will be 60 years. It is expected that the first unit of the power plant will generate electricity in 2023, and other units will be operating at one-year intervals until the end of 2026 (See Table 3.1) (IAEA-CNPP, 2021).

According to an agreement with Japan, there will be four units with ATMEA-1 type reactors and 1120 MW(e) capacity for each in the Sinop province at the end of 2030. Furthermore, there will be 4480 MW(e) total installed capacity, and each reactor's lifetime will be 60 years (IAEA-CNPP, 2021). It is expected that the first reactor will start generating electricity in 2025 (See Table 3.1); however, the power plant's construction was stopped due to the inconsistency of cost accounts.

Table 3.1 *Planned Nuclear Power Plants in Turkey. (IAEA-CNPP, 2021)*

Station/Project name	Type	Capacity	Expected construction start year	Expected commercial year
Akkuyu NPP - 1	WWER-1200	1200 MW(e)	2018	2023
Akkuyu NPP - 2	WWER-1200	1200 MW(e)	2019	2024
Akkuyu NPP - 3	WWER-1200	1200 MW(e)	2020	2025
Akkuyu NPP - 4	WWER-1200	1200 MW(e)	2021	2026
Sinop NPP - 1	ATMEA-1	1120 MW(e)	2020	2025
Sinop NPP - 2	ATMEA-1	1120 MW(e)	2021	2026
Sinop NPP - 3	ATMEA-1	1120 MW(e)	2024	2029
Sinop NPP - 4	ATMEA-1	1120 MW(e)	2025	2030

3.2 Review of the Related Legislation Regarding the Akkuyu-NPP

The first regulatory body in Turkey was established in 1956 as the Atomic Energy Commission with Law no.6821. Since then, Turkey has become one of the founding members of IAEA in the following year. In 1982, the Turkish Atomic Energy Authority (TAEA) was established by Law no.2690 to place the Atomic Energy Commission. From 1982 to 2018, TAEA operated as the main regulatory body in the field of peaceful uses of nuclear energy, including responsibilities of issuing regulations, doing safety reviews, granting permissions and licenses, conducting enforcement, etc.

The Turkish government system was transformed into a presidential republic in 2018, and all governmental institutions were modified to adapt to the new presidential system. During this transition, one important legislation affecting nuclear and radiation facilities and activities is the Decree-Law No. 702, issued by the cabinet on July 9th, 2018. The Decree-Law on Organization and Duties of Nuclear Regulatory Authority and Amendments to Certain Laws leading to establish a new independent nuclear authority called Nuclear Regulatory Authority (NRA) in Turkey is a comprehensive nuclear law regulating safety, security, safeguards, radiation protection, and other related subjects. Enacted on July 15th, 2018, Presential Decree No:4, the Decree Law on Organization of Institutions and

Organizations Related, Affiliated, and Associated with Ministries and Other Institutions and Organizations, defines the duties and responsibilities of NRA (Convention on Nuclear Safety, 2019). After establishing NRA, the former nuclear regulatory body, TAEA, was transformed into an R&D organization and named Turkish Energy, Nuclear and Mineral Research Agency (TENMAK) in 2020.

The Environmental Law (No.2872, 1983) and the Law on Electricity Market (No.6464, 2013) are other important legislations affecting nuclear installation. The Environmental Law regulates the environmental impact of nuclear facilities and gives the regulatory responsibilities and authorities to the Ministry of Environment Urbanization and Climate Change. The Law on Electricity Market regulates electricity production licenses and gives authority on electricity regulations to the Energy Market Regulatory Authority (EMRA) (Convention on Nuclear Safety, 2019).

Several regulations defining nuclear safety requirements and plans involving disaster response and radiation emergency exist in Turkey. These regulations and plans are continuously revised to adopt the new governmental system and its legislative structure. The revisions upgrade national regulations to new editions of the IAEA safety standards and adopt them to the safety objectives of the IAEA fundamentals and requirements. It is important to highlight Turkey's national disaster response and radiation emergency plan to understand the country perspective since the emergency action plan at the provincial level for Akkuyu-NPP is still in preparation.

3.2.1 National Disaster Response Plan (2014)

The need to improve an integrated national disaster response plan became inevitable after the Van Earthquake in October 2011. With the collective work of governmental and non-governmental stakeholders, the Turkish Disaster and Emergency Management Authority (DEMA) (*Afet ve Acil Durum Yönetimi Başkanlığı* – AFAD in Turkish) initiated the preparation of the national response plan. The plan was officially approved in January 2014 and named Turkey's National Disaster Response Plan (*Türkiye Afet Müdahale Planı* – TAMP in Turkish). The plan has a comprehensive approach regarding preparation, response, recovery phases, and flexible and modular structure, which help adapt to all types and scales of hazards. The plan also defines the responsibilities and roles of all key and supportive institutions participating in disaster and emergency response. Within the National Disaster Response Plan scope, 28 service groups are designated under four main categories: operation, information and planning, logistics and maintenance, finance, and administration services (NDRP, 2014). Evacuation planning for disasters and emergencies is regarded as part of the National Disaster Response Plan. Evacuation and Housing Planning Services Group, led by the Ministry of Interior, is assigned as a responsible service group for implementing evacuation actions during disasters and emergencies (NDRP, 2014).

3.2.2 National Radiation Emergency Plan (2019)

In April 2019, NRA prepared the National Radiation Emergency Plan (*Ulusal Radyolojik Acil Eylem Planı – URAP in Turkish*) was prepared by Nuclear Regulatory Authority (NDK) in collaboration with DEMA based on Turkey's National Disaster Response Plan (NREP, 2019). The National Radiation Emergency Plan defines all the responsible organizations, such as ministries, public institutions, and service groups, and their responsibilities in responding to radiation emergencies. Additionally, it explains radiation emergency planning bases, and technical guidelines align with the safety requirements of the IAEA (See section 2.2.1).

In the NREP, emergency planning zones, emergency planning distances, and areas to be cordoned are described for the nuclear facilities with larger than 1000 MW installed capacity. These are:

- 'Precautionary Action Zone' with 5 km radius
- 'Urgent Protective Action Zone' with 20 km radius

- ‘Extended Planning Distance’ with 100 km radius
- ‘Food and Trade Goods Restriction Distance’ with 300 km radius (NREP, 2019).

The dimensions of these emergency planning zones are defined as circles, and distances are expressed the length. However, their actual boundaries are determined by considering highways, rivers, district boundaries, and topographical features so that the public and emergency responders can easily understand them to carry out the protective actions effectively. The details of these zones and distances are provided and explained in the provincial radiation emergency plans (NREP, 2019). Moreover, the operating organization classifies nuclear power plant emergencies by considering the Emergency Action Levels (EALs), which are predetermined variables for each emergency class and are specific to each plant type, for rapid and accurate identification of nuclear emergencies. The classification system is based on the possibility of high radiation release occurring on-site and off-site caused by damaged reactor building, reactor core, etc. The emergency classification aims to provide sufficient time for the on-site emergency response organizations to mitigate the risk and for off-site emergency response organizations to implement protective actions (NREP, 2019). According to the NREP, there are four emergency classes related to possible off-site nuclear power plant emergencies:

- general emergency
- site area emergency
- facility emergency
- alert.

‘General emergency’ covers situations with a major release or exposure of radioactive material. When the general emergency is declared, the required actions for mitigation of consequences and protective actions must be taken urgently for people on-site and in emergency planning zones (NDRP, 2014). This study is prepared by considering the possibility of a general emergency in the Akkuyu Nuclear Power Plant.

Different types of protective actions are being used with different combinations depending on the severity of nuclear emergencies: using iodine tablets, shelter in place, evacuation of the contaminated area, etc. (General Safety Requirements No. GSR Part 7, 2015). Iodine tablets used as one of the protective actions are non-radioactive iodine compounds distributed with their instruction manual before the radioactive release. The amount of iodine tablets as mg depends on the chemical forms of iodine, age, being pregnant, and being a breastfeeding mother or not. Using iodine tablets protects the thyroid gland against radioactive iodine for almost 24 hours. People should take iodine tablets before 1-6 hours of radioactive exposure for maximum protection. After 24 hours, it may be necessary to take another iodine tablet if the high amount of radioactive iodine is still in the air; however, it is not recommended to use iodine tablets more than once. In this regard, shelter in place should be restricted to 1 day in the contaminated areas (NREP, 2019).

IAEA (2013) recommends using iodine tablets and sheltering first since the evacuation cannot be implemented safely during an emergency due to various reasons such as blocked routes and special facilities which are hard to evacuate. However, US NRC (1987) states that evacuation performed at walking velocities and above is more effective than sheltering. This study focuses on the idea of evacuating the site rather than sheltering and using iodine tablets since sheltering is not recommended for more than 1 day in the contaminated area, and using iodine tablets is not recommended to use more than once in NREP.

Radiation Protection

The Regulation on Radiation Protection in Nuclear Facilities, enacted in 2018, is accepted as the main regulatory document regarding the radiation protection aspects in the nuclear power plant. In a full report to the 8th Review Meeting of the Convention on Nuclear Safety (2019), this Regulation reflects the latest developments in the nuclear power program in Turkey. It also includes all requirements to protect the workers, the public, and the environment from the harmful effects of ionizing radiation during the site assessment, design, construction, commissioning, operation, de-commissioning, and exemption of the nuclear facilities and during nuclear emergencies. Besides, the regulation separately identifies the dose constraints for the public, the workers, and the environment and the limits for gaseous and liquid wastes. Moreover, it indicates that monitoring and recording radiation concentration in air, water, soil, and various food samples in regular intervals and dose rates in the environment continuously within the scope of the environmental monitoring program as indispensable (Convention on Nuclear Safety, 2019).

Emergency Preparedness

Turkey has frequently faced different types of disasters, such as earthquakes, landslides, floods, and rockfalls that lead to human, material, economic, and environmental losses. In 2009, DEMA was established as a national coordinating authority for all kinds of disasters and emergencies at all levels, including large-scale nuclear emergencies (Convention on Nuclear Safety, 2019). In addition, Provincial Disaster and Emergency Directorates (PDED) were affiliated with the DEMA within the body of governorship in different provinces to make a hazard assessment and prepare and implement a provincial disaster and emergency plan (Convention on Nuclear Safety, 2019). Furthermore, the NRA, which undertakes regulatory and inspection activities within the scope of nuclear emergency preparedness, is responsible for radiation emergency management (Convention on Nuclear Safety, 2019).

Akkuyu Nuclear JSC is responsible for developing the on-site radiation emergency action plan. The Draft Regulation on Management of the Nuclear and Radiological Emergencies clearly defines the requirements of the on-site emergency plans. It classifies and identifies the emergency, determines responsibilities for response activities, arrangements of alarms, protection of emergency workers from radiation, radiological monitoring in the facility, on-site and near the site, information to be ensured for off-site emergency response organizations and the public, and mitigation of the consequences (Convention on Nuclear Safety, 2019).

The Governorships of provinces where nuclear power plants are located are responsible for developing Provincial Radiation Emergency Action Plans associated with the National Disaster Response Plan (NDRP) and National Radiation Emergency Plan (NREP). These plans cover the off-site radiation emergency action involving the response actions (i.e., evacuation planning) to protect the public and the environment during radiological emergencies. In this context, Mersin Governorship is responsible for preparing the provincial radiation emergency action plan for the Akkuyu Nuclear Power Plant; however, the emergency plan has not been completed yet (Convention on Nuclear Safety, 2019).

3.3 Project Details of the Akkuyu-NPP

Akkuyu NPP is located within the provincial boundary of Mersin in the southern part of Turkey, with 1,891,145 people according to the 2021 values by the Turkish Statistical Institute (TURKSTAT) between Antalya and Adana Provinces (Site Evaluation Report for Akkuyu NPP, 2013). The central geographical coordinates of the power plant are 36°08′40′′ N and 33°32′28′′ E (Akkuyu NPP Site Report Volume 1, 2013). The project site is located in the Gülnar district (See Figure 3.1), with the highest population growth rate of 8,94% within Mersin Province according to the population comparison of 2020 and 2021 by TURKSTAT. Gülnar district is placed at a plain high in the Taurus Mountains, along the road connecting Central Anatolia to Anamur. While Gülnar district center is 25 km away, Mersin city center is 140 km away from the project site (EIA Report for Akkuyu NPP, 2013). Adana-Antalya highway is the closest highway, and the project site is connected to this highway via a 4.5 km long road. Büyükeceli town, located 3,5 km Northeast of the center of Akkuyu NPP, is the closest settlement to the Akkuyu site (Site Evaluation Report for Akkuyu NPP, 2013). Up to 200 m high hills surrounded the project site, and they formed the natural boundary of the NPP project area.

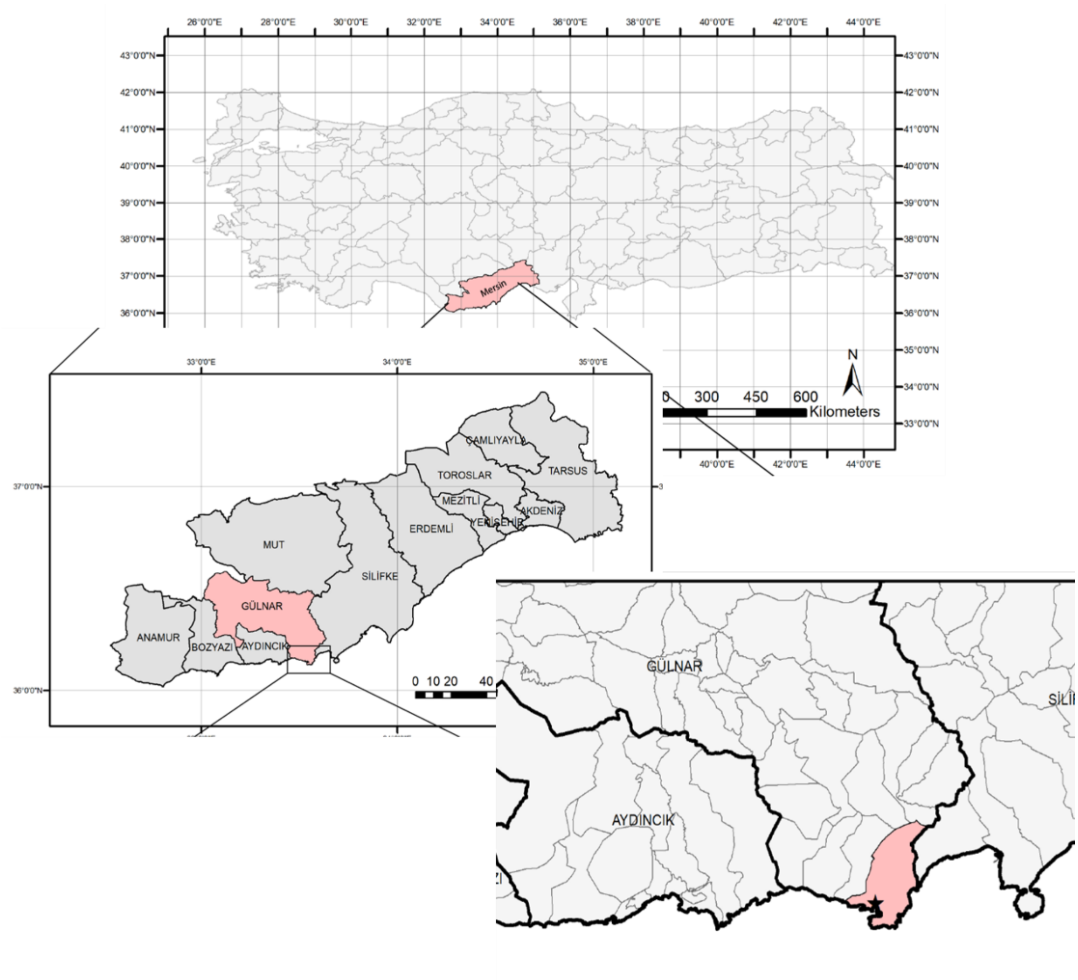

Figure 3.1. Akkuyu-NPP Site Accommodation

3.3.1 Physical Features of the Akkuyu-NPP

According to the Environmental Impact Assessment (EIA) report of Akkuyu NPP (2013), the area size of the project site covers 1,023 hectares of land. In addition, it is planned to construct a living center on an area of 35 hectares to accommodate the personnel working in the operation of Akkuyu NPP and their families. This accommodation area is located outside but adjacent to the borders of the project site (See Figure 3.2). The preliminary design of the accommodation area consists of 2,000 flats, a limited number of villas, a 500-room dormitory, and a 250-room guesthouse. The living center is expected to provide accommodation for 3,000 permanent staff and 1500 family members who are expected to settle in the region. Thus, 4,500 residents are expected to be accommodated in the living center (EIA Report for Akkuyu NPP, 2013).

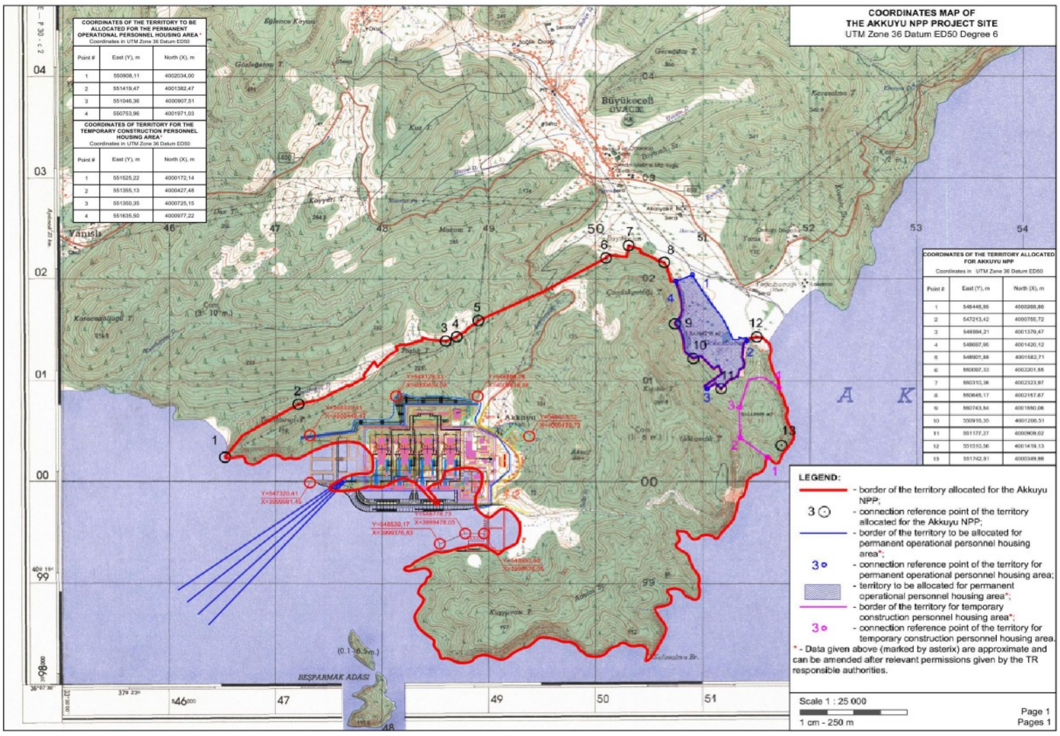

Figure 3.2. Site layout of the Akkuyu-NPP (Akkuyu-NPP Site Report, 2013, p.52)

Akkuyu Nuclear Power Plant project based on Russian PWR-designed VVER-1200 technology has been started to be built in Akkuyu site by an Inter-Governmental Agreement between the Republic of Turkey and the Russian Federation (Site Evaluation Report for Akkuyu NPP, 2013). According to the Inter-Governmental Agreement, it is planned to build four units with VVER-1200 type reactors and 1200 MW(e) capacity for each (See Figure 3.3). The total installed capacity is 4800 MW(e), and the lifetime for each unit is designed as 60 years. It is expected that the first unit of the power plant will generate electricity in 2023, and other units will be operating at one-year intervals until the end of 2026 (IAEA-CNPP, 2021).

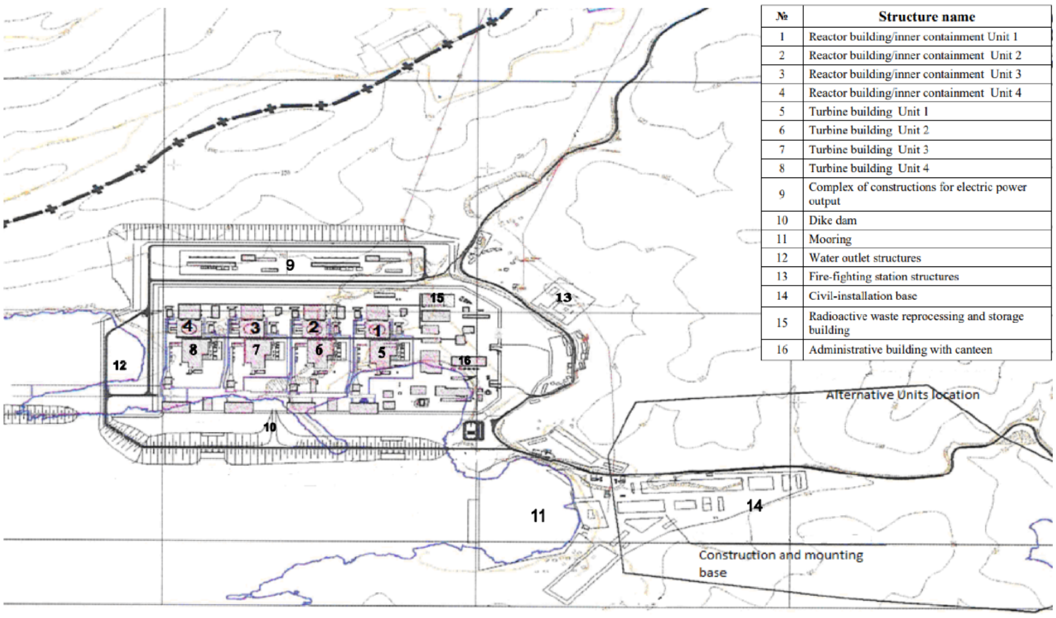

Figure 3.3. Main layout scheme of the Akkuyu-NPP (Akkuyu-NPP Site Report, 2013, p.41)

3.3.2 Environmental Impact Assessment (EIA) Report for the Akkuyu-NPP

In the environmental impact assessment (EIA) report for Akkuyu Nuclear Power Plant (2013), the existing transport network for evacuation is declared as 5-kilometer-long asphalt paved roads connecting the Büyükeceli Municipality. Büyükeceli, located to the northeast of the Akkuyu Nuclear Power Plant, is 2,5 km away from the NPP site. This road connects the Akkuyu NPP site to the Adana-Antalya highway. The closest airport is 200 km from the Akkuyu NPP site and is in Adana province. The closest railway is 110 km away from the Akkuyu NPP site and is in Tarsus, one of the districts of Mersin province. There is a Silifke-Taşucu ferry dock 32 km away from the Akkuyu NPP site and Mersin port 110 km away from the Akkuyu NPP site as the closest water transportation. In this regard, other transportation routes are not suitable for evacuation from emergency planning zones during nuclear emergencies apart from highways and potential water transportation (EIA Report for Akkuyu NPP, 2013). Moreover, the existing transportation network has several undesirable features obstructing the emergency response actions, which are:

1. Insufficiency of alternative transportation routes,
2. Limited access to the residential area near the Akkuyu NPP site,
3. Topographic features indigenous to the region contribute to the increase in nuclear contamination concentration in nuclear emergencies. (EIA Report for Akkuyu NPP, 2013)

According to the EIA Report (2013), the Akkuyu NPP Project will cover transportation infrastructure development, alternate routes for evacuation, and a road linking the facility and the residential area nearby. Besides, two piers will be constructed for the equipment delivery. It may be regarded as alternate water transportation for the evacuation of workers during nuclear emergencies (EIA Report for Akkuyu NPP, 2013).

When the current regulations, plans, and reports explaining the actions and precautions for nuclear power plant emergencies in Turkey are examined, it is seen that these documents do not include detailed and sufficient information about evacuation planning in case of nuclear emergencies.

CHAPTER 4

METHODOLOGY

The following chapter presents the methodology used in the atmospheric dispersion modeling and nuclear hazard mapping for Akkuyu Nuclear Power Plant. The chapter explains the necessary parameters for atmospheric dispersion modeling, the sensitivity analysis of HySPLIT, and the hazard mapping process.

4.1 Study Framework

This research provides the initial steps of evacuation planning in the emergency preparedness phase for the hypothetical accident in the Akkuyu Nuclear Power Plant. Firstly, it models the atmospheric dispersion of Cs-137 and I-131 within the hypothetical accident, considering the source term parameter under three different meteorological conditions. Then it creates the nuclear hazard maps by superposing the atmospheric dispersion models for each scenario to identify the evacuation zones. Lastly, it classifies the radiation exposure risk within the evacuation zones based on total exposure time to ambient dose and overlaps with the geographical distribution of the population to estimate the evacuation demand. The methodology diagram of the research is shown in Figure 4.1.

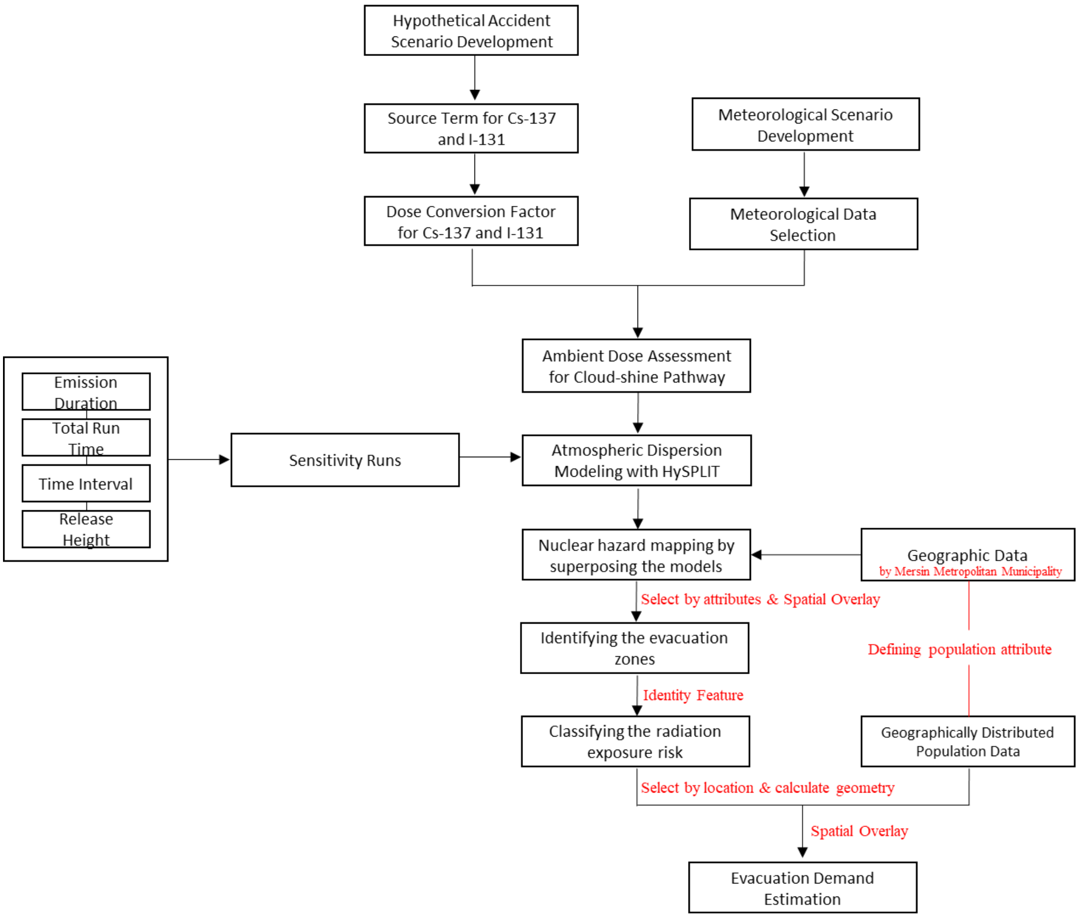

Figure 4.1. Methodology diagram of the research

4.2 Hypothetical Accident Scenario Development

This research performs a dose assessment of radioactivity release to the environment via atmospheric dispersion under a hypothetical accident scenario for the Akkuyu-NPP. Various scenarios were defined in the literature to predict the potential risks that are likely to occur caused by potential nuclear power plant accidents in a better way(Bilgiç, 2016). For example, Fairuz and Sahadath (2020) studied a hypothetical accident at the proposed Rooppur Nuclear Power Plant (RNPP) in Ishwardi, Pabna, Bangladesh. The RNPP is currently under construction, and the first two units are expected to start generating electricity in 2023 and 2024, respectively. The proposed RNPP is based on VVER-1200 AES 2006 model, a GEN III+ reactor (Fairuz &

Sahadath, 2020). The Akkuyu NPP has the same technology as the RNPP. For this reason, this research considers the hypothetical accident scenario and the source term used in the study of RNPP valid for the simulation to be conducted for the case of Akkuyu-NPP.

As the hypothetical accident scenario, this research accepts a large break loss of coolant accident (LBLOCA) along with a station blackout (SBO) in one of the reactor units of Akkuyu NPP. This accident scenario assumes that the Emergency Core Cooling System (ECCS), which helps remove residual heat from the reactor fuel rods in the event of a failure of the normal core cooling system, is unavailable. These combined effects cause the rapid depressurization in the core leading to the formation of steam. In the end, the core starts to melt, and the fission products are released into the containment via the break. Since SBO leads all the filtration and ventilation systems to be dysfunctional, the fission products in the containment start to escape via the vent stack due to failed closure of the isolation valve in the ventilation system. In this hypothetical accident scenario, which is the in-vessel core melting accident, this research assumes that there will be no reduction mechanism working, and the ex-vessel melt retention (EVMR) technology of the VVER-1200 reactor was not in service. In terms of activity released, the hypothetical accident scenario in this research resembles INES level 7, defined as a major accident. (Fairuz & Sahadath, 2020).

4.3 Source Term Parameters

The source term for the atmospheric dispersion modeling is obtained from the work of Afrida Fairuz and Md. Hossain Sahadath (2020 since Akkuyu NPP and Rooppur NPP have AES 2006 model GEN III+ VVER-1200 type reactor with 3200 MW thermal power. The following simple equation has been used for the source term (ST) calculation.

$$ST = \left[\left\{ \frac{\text{Activity(Ci)}}{MW_{th}} \right\} \times (3200 \ \ MW_{th}) \times RF \times RDF \times EF \right]$$

(Eq.4.1)

where,

Activity (Ci)/MW_{th} = Core inventory factor (Initial activity per megawatt thermal for the individual radionuclides)

Core Thermal Power = 3200 MW_{th}

RF = Release Fraction

RDF = Reduction Factor

EF = Escape Fraction

The core inventory factor of the individual radionuclides is taken from the work done by the US NRC staff in December 2003. It is calculated by using the SAS2H control module of standardized computer analysis for licensing evaluation, Version 4.4a. The release fraction has different dependencies: the physical and chemical forms of the radionuclides, the level of conservatism used, and the type of nuclear accident scenarios. (IAEATECDOC-643, 1992) In this work, the release fractions (RF) are obtained from the report, namely NUREG-1465, regarding the case of a predefined accident scenario. Since no reduction mechanisms will work according to the predefined scenario, the reduction factor (RDF) and the escape fraction (EF) are not considered. In other words, they will be equal to 1. The release height and the release duration are other important source term parameters, and they are determined by the sensitivity analysis. Fairuz and Sahadath (2020) study calculated the source term for 49 radionuclides selected from the literature based on VVER-1000 (Jafarikia & Feghhi, 2018). Table 4.1. presents the actual activity levels of eight radionuclide groups determined by the US NRC. In this research, only Cs-137 and I-131 are taken into account. The calculated activity levels of Cs-137 and I-131 are used together with pre-defined meteorological data and other source term parameters, which are the release duration and release height, combined in the atmospheric dispersion model HySPLIT.

In addition, implementing the limitation principles against radiation exposure requires an effective dose assessment. The dose rate coefficients are intended for calculating age-specific effective doses from external exposure to radionuclides in the environment. It is required to compare the ambient dose rate and evacuation dose limit in the regulatory context in identifying the evacuation zones. Therefore, the air concentration value calculated by the atmospheric dispersion model and dose conversion factor obtained from the FGR-15 (See appendix A) is combined in HySPLIT within the scope of this research. The dose conversion factors are obtained regarding the cloud-shine dispersion pathway and adult reference person. Consequently, it obtains the ambient dose rates to create nuclear hazard maps.

Table 4.1 S*ource term for hypothetical accident considered in this study (Fairuz & Sahadath, 2020, p.3)*

Group	Radionuclides	Ci/MW_{th}	Core Thermal Power, (*MW*)	Release Fraction	Activity Released (*Ci*)	Activity Released (*Bq*)
Noble Gas	Kr-83m	3.05E+03	3200	1.0	9.76E+06	3.61E+17
	[a]Kr-85	4.32E+02		1.0	1.38E+06	5.12E+16
	Kr-85m	6.17E+03		1.0	1.97E+07	7.31E+17
	Kr-87	1.23E+04		1.0	3.94E+07	1.46E+18
	Kr-88	1.70E+04		1.0	5.44E+07	2.01E+18
	Xe-131m	3.65E+02		1.0	1.17E+06	4.32E+16
	Xe-133	5.43E+04		1.0	1.74E+08	6.43E+18
	Xe-133m	1.72E+03		1.0	5.50E+06	2.04E+17
	Xe-135	1.42E+04		1.0	4.54E+07	1.68E+18
	Xe-135m	1.15E+04		1.0	3.68E+07	1.36E+18
	Xe-138	4.56E+04		1.0	1.46E+08	5.40E+18
Halogen	I-131	2.67E+04		0.4	3.42E+07	1.26E+18
	I-132	3.88E+04		0.4	4.97E+07	1.84E+18
	I-133	5.42E+04		0.4	6.94E+07	2.57E+18
	I-134	5.98E+04		0.4	7.65E+07	2.83E+18
	I-135	5.18E+04		0.4	6.63E+07	2.45E+18
Alkali Metal	[a]Cs-134	7.31E+03		0.30	7.02E+06	2.60E+17
	Cs-136	1.49E+03		0.30	1.43E+06	5.29E+16
	[a]Cs-137	5.05E+03		0.30	4.85E+06	1.80E+17
	Rb-86	5.29E+01		0.30	5.08E+04	1.88E+15
Tellurium	Te-127	2.36E+03		0.05	3.78E+05	1.40E+16
	Te-127m	3.96E+02		0.05	6.34E+04	2.34E+15
	Te-129	8.26E+03		0.05	1.32E+06	4.89E+16
	Te-129m	1.68E+03		0.05	2.69E+05	9.95E+15
	Te-131m	5.41E+03		0.05	8.66E+05	3.20E+16
	Te-132	3.81E+04		0.05	6.10E+06	2.26E+17
	Sb-127	2.39E+03		0.05	3.82E+05	1.41E+16
	Sb-129	8.68E+03		0.05	1.39E+06	5.14E+16
Ba/Sr Group	Ba-140	4.76E+04		0.02	3.05E+06	1.13E+17
	Sr-89	2.41E+04		0.02	1.54E+06	5.71E+16
	[a]Sr-90	3.72E+03		0.02	2.38E+05	8.80E+15
	Sr-91	3.01E+04		0.02	1.93E+06	7.13E+16
	Sr-92	3.24E+04		0.02	2.07E+06	7.67E+16
Noble Metal	Mo-99	5.30E+04		0.0025	4.24E+05	1.57E+16
	Ru-103	4.34E+04		0.0025	3.47E+05	1.28E+16
	Ru-105	3.06E+04		0.0025	2.45E+05	9.06E+15
	[a]Ru-106	2.41E+04		0.0025	1.93E+05	7.13E+15
	Rh-105	2.81E+04		0.0025	2.25E+05	8.32E+15
	Tc-99m	4.37E+04		0.0025	3.50E+05	1.29E+16
Cerium Group	Ce-141	4.39E+04		0.0005	7.02E+04	2.60E+15
	Np-239	5.69E+05		0.0005	9.10E+05	3.37E+16
	[a]Pu-241	6.62E+03		0.0005	1.06E+04	3.92E+14
Lanthanides	Cm-242	1.12E+03		0.0002	7.17E+02	2.65E+13
	La-140	4.91E+04		0.0002	3.14E+04	1.16E+15
	Nd-147	1.75E+04		0.0002	1.12E+04	4.14E+14
	Pr-143	3.96E+04		0.0002	2.53E+04	9.38E+14
	Y-90	2.45E+03		0.0002	1.57E+03	5.80E+13
	Zr-95	4.44E+04		0.0002	2.84E+04	1.05E+15
	Zr-97	4.23E+04		0.0002	2.71E+04	1.00E+15

[a] Long lived radionuclide (Half life >1 year).

4.4 Meteorological Data Selection

This research identifies three scenarios for different meteorological conditions prevailing around the Akkuyu NPP reactor site. It uses the weekly GDAS data with 1° x 1° grid resolution belonging to 2021 to detect the simulation period of this study. Since the GDAS provides the gridded meteorological data, this research considers the data in the nearest grid coordinates to the Akkuyu NPP. The research identifies scenarios by comparing the wind parameters within the meteorological data for 52 weeks of the year 2021. It creates the wind rose diagram (Figure 4.2), indicating wind directions with wind speeds, and the wind frequency graph to select suitable simulation periods for 2021 (Figure 4.3).

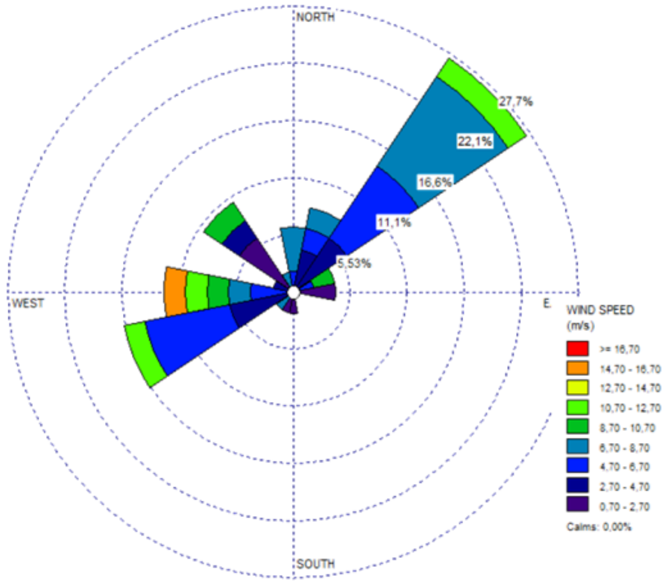

Figure 4.2. The wind rose diagram indicating wind directions (blowing from) and speeds in Mersin Province in 2021

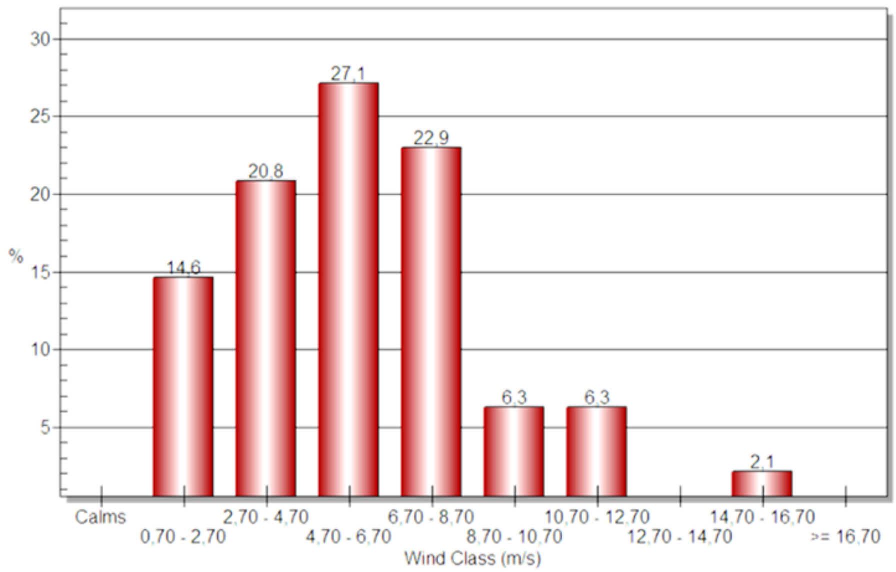

Figure 4.3. Wind Class Frequency Distribution in Mersin Province, 2021

Since this study investigates the evacuation zones during and after the following pre-defined hypothetical nuclear power plant accident in Akkuyu, it determines the simulation periods according to the wind directions blowing from the sea to the inland (See Figure 4.4). The wind directions blowing from the inland to the sea that will affect the marine environment is considered beyond the scope of this thesis.

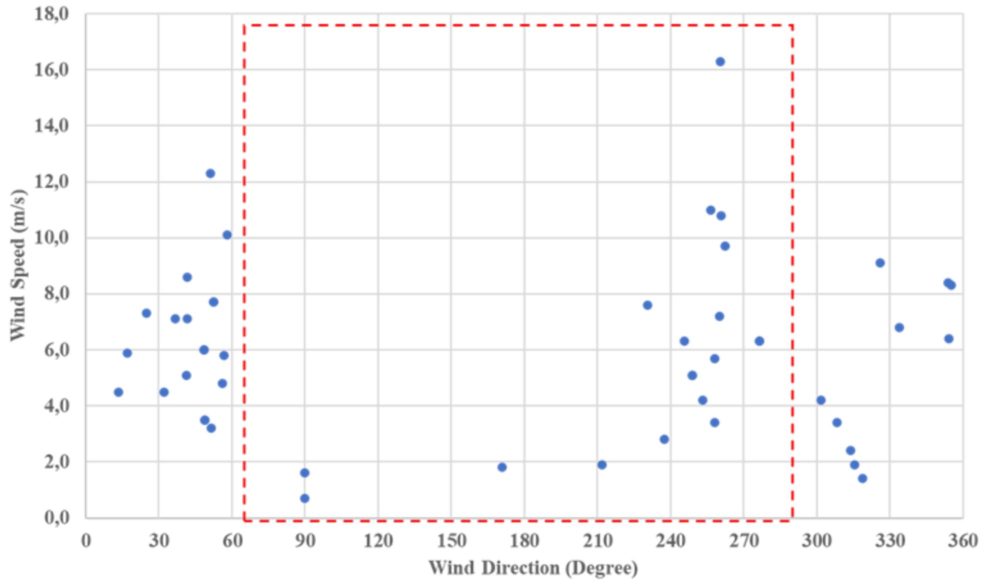

Figure 4.4. Scatterplot indicating the wind speeds and directions blowing from the sea to the inland in Mersin Province, 2021

As the turbulence factor and the vertical pressure levels of the wind affects the plume direction, 52 weeks of the year 2021 are simulated with HySPLIT to observe the highest ambient dose distribution through the inland. Then, the corresponding weeks of the months with the low average and the highest wind speed are selected to be the simulation period. The model is run for three time periods for Akkuyu NPP:

i. 08-11 February 2021

ii. 15-18 May 2021

iii. 01-04 December 2021.

The first period (08-11 February 2021) corresponds to the low wind speed (1.9 m/s) blowing from the sea to the inland in the west direction, representing the low meteorological condition. The second period (15-18 May 2021) corresponds to the average wind speed (5.1 m/s) blowing from the sea to the inland in the east direction, representing the average meteorological condition. The third period (01-04 December 2021) corresponds to the highest wind speed (16.3 m/s) blowing from the sea to the inland in both the east and west direction, representing the extreme meteorological condition. Any kind of precipitation is not considered since this study does not investigate wet deposition.

4.5 Atmospheric Dispersion Modeling using HySPLIT

The modeling part of the study consists of two steps. At first, several sensitivity runs are performed in HySPLIT with constant source term and simulation period with average meteorological condition (scenario 2) to determine how different source term parameters affect the ambient dose rate. Subsequently, the actual atmospheric dispersions of the cumulative ambient dose for Cs-137 and I-131 are modeled in HySPLIT with the combination of the selected parameters by sensitivity runs, defined dose conversion factors, and three different meteorological conditions.

The accident scenario and the source term, provided by the work of Fairuz and Sahadath (2020), are regarded as constant in sensitivity runs and actual simulations. According to Fairuz and Sahadath's (2020) research, the source term is calculated regarding the core inventory factor, release fraction by a predefined accident scenario, core thermal power of VVER-1200 type reactor unit, reduction factor, and escape fraction by using the SAS2H control module of standardized computer analysis for licensing evaluation, Version 4.4a. The source terms calculated for Cs-137 and I-131 are 1.80E+17 Bq and 1.26E+18 Bq, respectively. Two radionuclide groups are defined in HySPLIT: the first is for Cs-137, representing alkali metals, and the second is for I-131 representing halogens. The dose conversion factors are obtained regarding the cloud-shine dispersion pathway and adult reference person from FGR-15 (See Appendix A) as 3.89E-16 for Cs-137 and 1.69E-14 for I-131. Moreover, all sensitivity runs and actual atmospheric dispersion models are performed by using the GDAS data with a 1-degree resolution.

4.5.1 Sensitivity Analysis

This research performs sensitivity analysis to observe the effects of the input parameters on ambient dose rate and to determine the conditions that would result in the highest ambient dose rate before performing the actual simulations to determine the evacuation zones. Since there are various input parameters for atmospheric dispersion modeling of radionuclides, several sensitivity runs are performed with a constant source term and dose conversion factors to determine how different source term parameters affect the ambient dose rate. For the sensitivity analysis, the average meteorological condition is selected as the simulation period of May 15th - May 21^{st,} 2021. The parameters selected for sensitivity runs are emission duration and release height to observe the highest ambient dose rate. Moreover, the model is run with different total run times to determine how many hours are sufficient to observe the ambient dose rate. Additionally, the program is run at different time intervals to observe the HySPLIT outputs whether it provided sufficiently sensitive results or not.

The first sensitivity run is performed for six different emission durations with 108 hours total run time and 6 hours interval to observe the effect of emission duration on the cumulative ambient dose rate of Cs-137 and I-131. For emission duration parameter, six different models are run in 48 hours, 24 hours, 12 hours, 6 hours, 3 hours and 1 hour emission duration with 108 hours total run time, and 6 hours interval (See Table 4.2). The comparison of the results are shown in Figure 4.5. Since it is observed that the dose assessment result still have the highest ambient dose rate after 42 hours, 48 hours emission duration is selected for actual simulation. In other words, it is assumed that the whole volume of the containment release to the atmosphere in 48 hours.

Table 4.2 *The Values of Different Emission Durations and Total Run Times Used in HySPLIT for Sensitivity Runs*

	Emission Duration (hrs) Total Run Time (hrs) Interval (hrs)	Emission Duration (hrs) Total Run Time (hrs) Interval (hrs)	Emission Duration (hrs) Total Run Time (hrs) Interval (hrs)
Sensitivity run with different emission duraiton	48 108 6	24 108 6	12 108 6
	6 108 6	3 108 6	1 108 6
Sensitivity run with different total run time	48 108 6	48 72 6	48 48 6

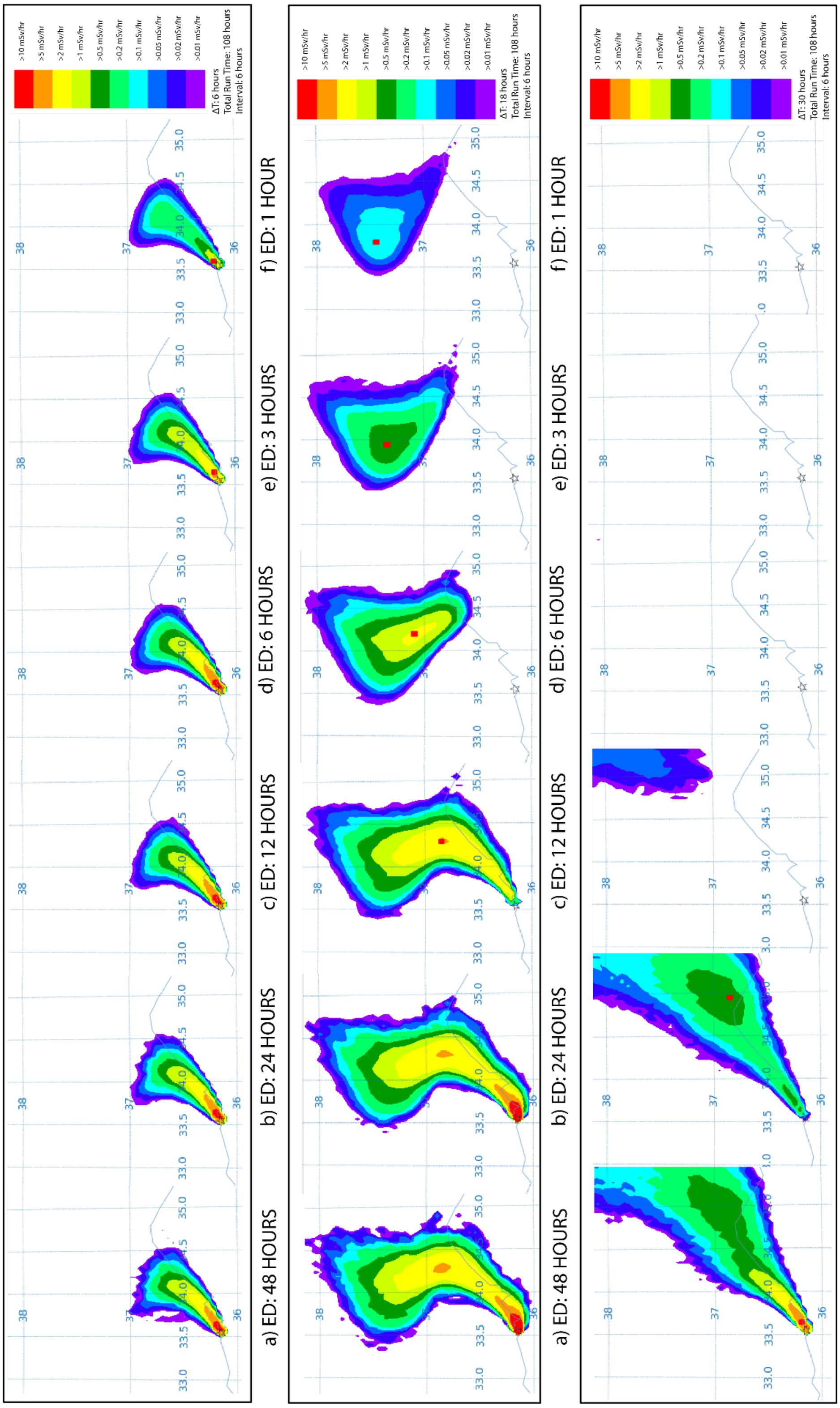

Figure 4.5. Sensitivity run for six different emission durations

The second sensitivity run is performed for three different total run times to determine how many hours of observation is necessary for 48 hours emission duration.To determine the sufficient total run time for the observation of the 48 hours emission, three models are run and compared in three different total run time, 108 hours, 72 hours and 48 hours with 6 hours interval (See Figure 4.6). After 48 hours, it is observed that the emission continues. For this reason, it is concluded that the ambient dose should be observed more than 48 hours. The 72- and 108-hours total run time comparison indicates that the observed ambient dose rate is too low than evacuation threshold value after 72 hours. Hence, 72 hours total run time is regarded as sufficient for this study.

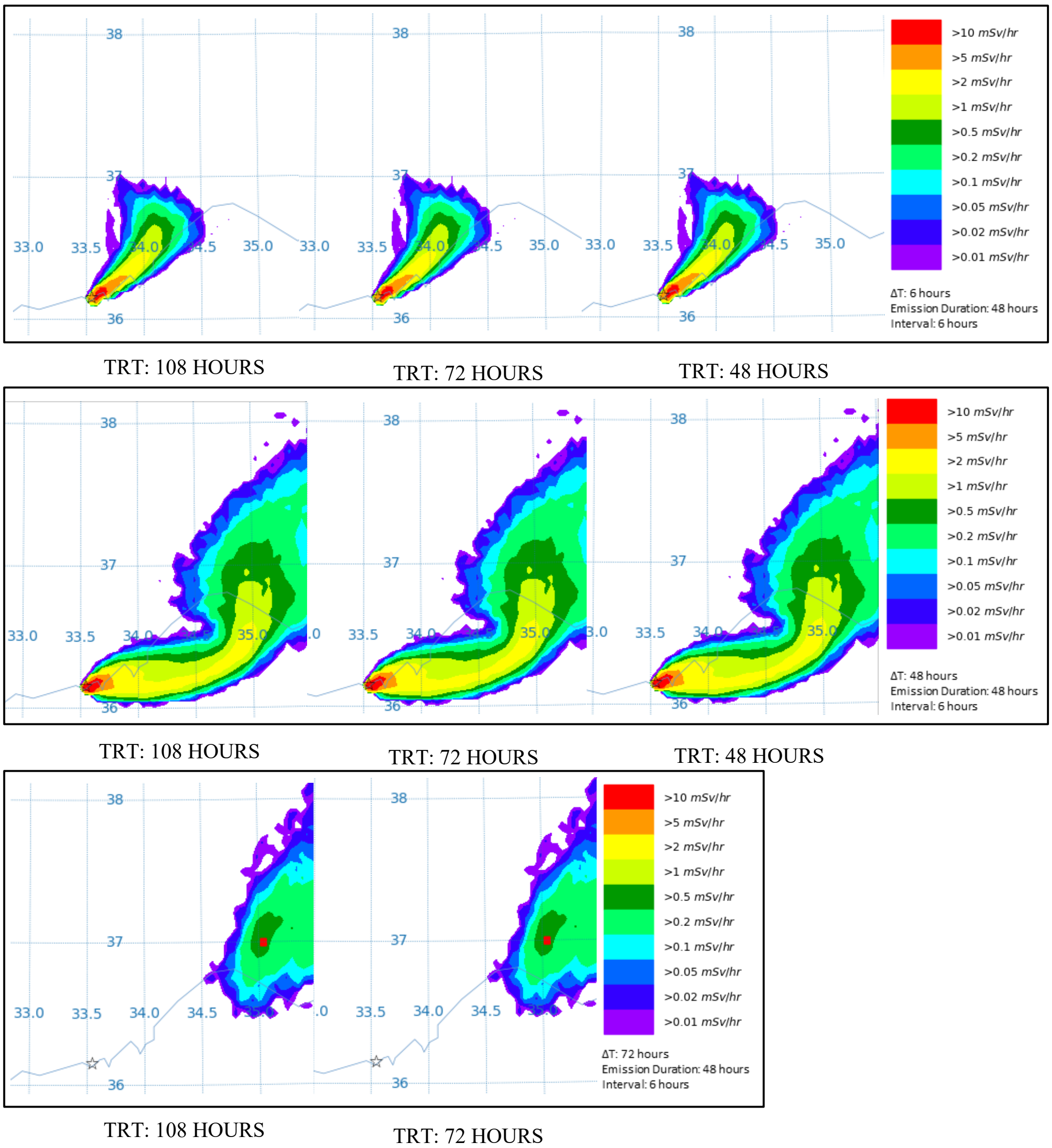

Figure 4.6. Sensitivity run for three different total run time

The third sensitivity run is performed for four time-intervals with 48 hours emission duration and 72 hours total run time (See Table 4.3) to determine which one presents the precise results for the following step of this study, i.e. evacuation zoning. The comparisons of the model with different time-intervals are shown in Figure 4.7. Four different models are run and compared to observe whether the HySPLIT provides sensitive outputs in different time-intervals or not. HySPLIT is run in 6 hours, 4 hours, 3 hours and 2 hours interval with 48 hours emission duration and 72 hours total run time, and the outputs are compared after 12 hours from the release start. According to the comparison, it is observed that 6 hours interval provides rougher outputs while 2 hours interval provides more detailed outputs. The comparisons between the results with 4 hours and 3 hours interval indicates similar outputs in terms of precision. Since the default threshold value for evacuation is calculated by the IAEA considering an unshielded person who has been exposed to the plume for 4 hours, 4 hours interval is used for the actual simulations in this study.

Table 4.3 *The Values of Different Time-Intervals Used in HySPLIT for Sensitivity Runs*

	Emission Duration (hrs) Total Run Time (hrs) Interval (hrs)	Emission Duration (hrs) Total Run Time (hrs) Interval (hrs)	Emission Duration (hrs) Total Run Time (hrs) Interval (hrs)
Sensitivity run with different time interval	48 72 6	48 72 3	48 72 2

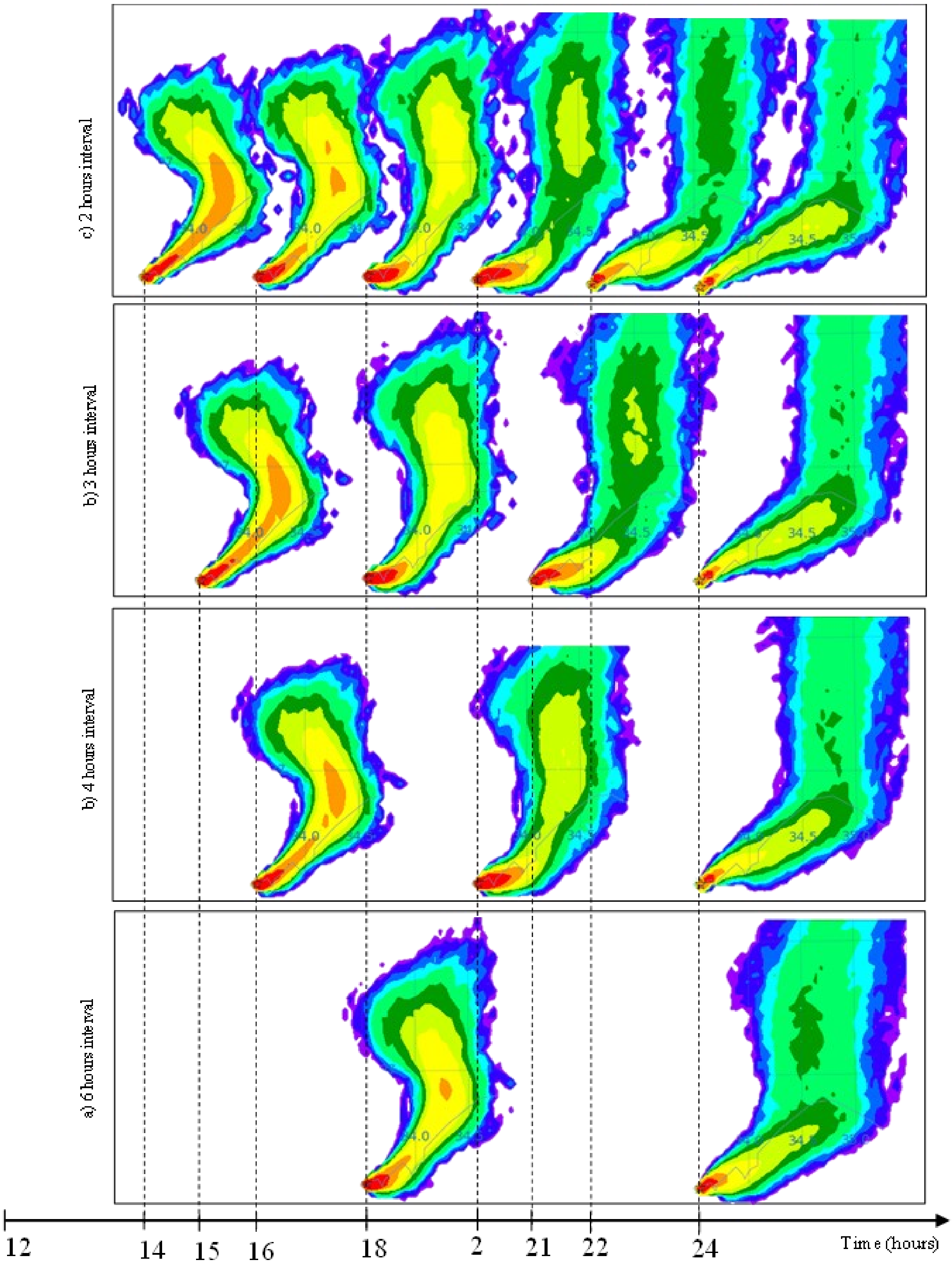

Figure 4.7. Sensitivity run with three different time-intervals

Another important source term parameter affecting the transport of radionuclides into the atmosphere is the initial release height of the plume. Hence, the release height is observed at two different levels, 100 m and 800 m (See Table 4.4) in order to determine the effect of release height on the ambient dose rate. The models are run with 48-hours emission duration, 72-hours total run time and 3-hours interval at two different levels. The compared results are shown in Figure 4.8. To sum up, the comparison of the results indicates that the 100-meter release height leads to the highest dose. That is, 100-meter release height is regarded as suitable for the predefined catastrophic nuclear power plant accident scenario.

Table 4.4 *The Values of Different Release Height Used in HySPLIT for Sensitivity Runs*

	Emission Duration (hrs) Total Run Time (hrs) Interval (hrs) Release height (m)	Emission Duration (hrs) Total Run Time (hrs) Interval (hrs) Release height (m)
Sensitivity run with different release height	48 72 3 100	48 72 3 800

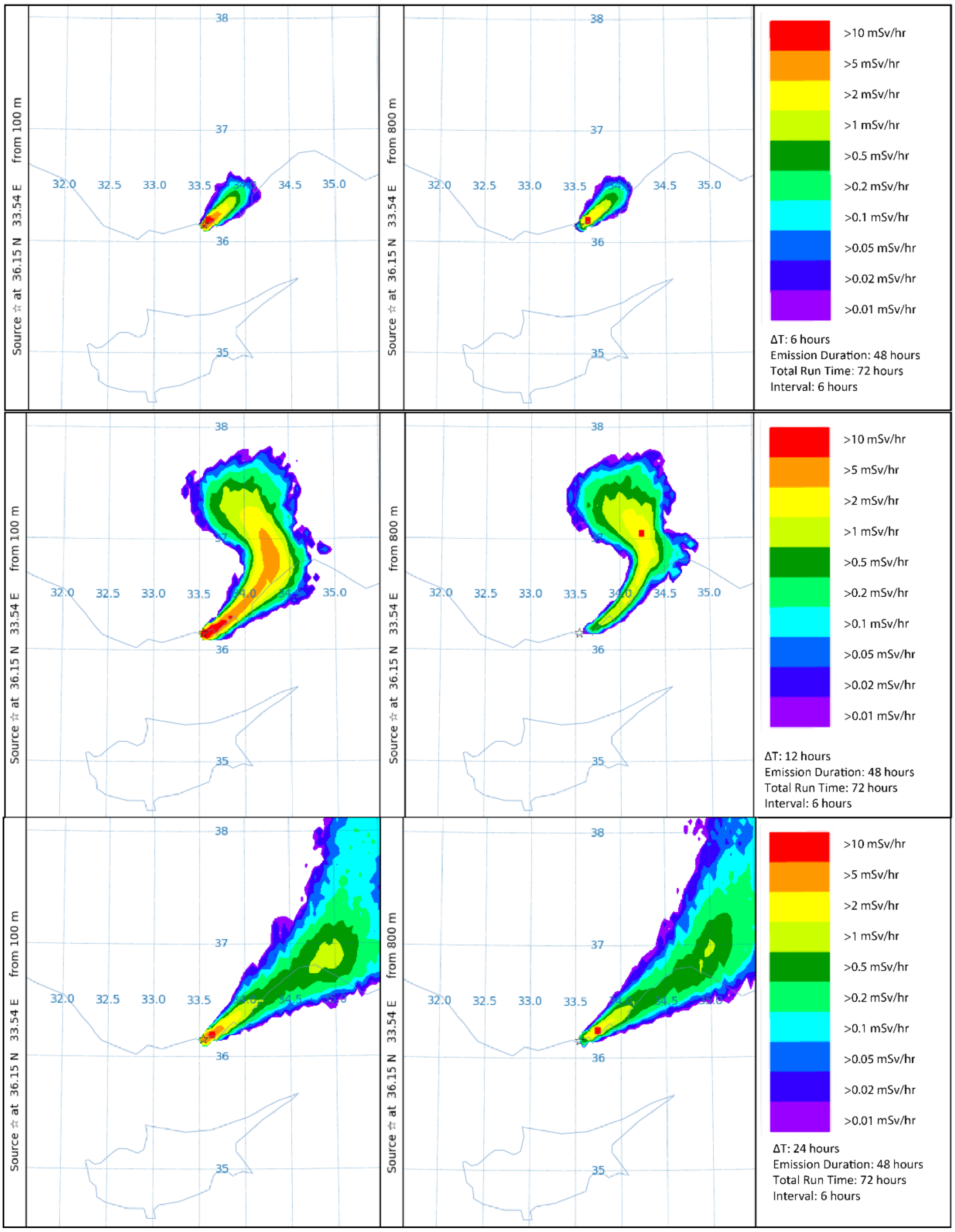

Figure 4.8. Sensitivity run with different release height

4.5.2 Atmospheric Dispersion Models for the Akkuyu-NPP

Following the sensitivity analysis, the atmospheric dispersion of ambient dose rate is modeled in case of a hypothetical accident in Akkuyu Nuclear Power Plant with 48 hours emission duration, 100 m release height, 72 hours total run time, and 4-hours interval and three different dispersion patterns are observed within the scope of predefined scenarios. As a result, there are eighteen atmospheric dispersion models classified by ten ambient dose rates: 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02, and 0.01 mSv/h. (See Appendix B) are obtained for three scenarios. The values of HySPLIT input data are shown in Table 4.5, and the outputs belonging to the first 4-hours of scenarios are indicated in Figure 4.9.

Table 4.5 *The Values of HySPLIT Input Data for the Actual Simulation for the Accident at Akkuyu Nuclear Power Plant*

	Scenario 1		Scenario 2		Scenario 3	
	Cs-137	I-131	Cs-137	I-131	Cs-137	I-131
Start Time (yy mm dd hh)	21 02 08 12	21 02 08 12	21 05 15 12	21 05 15 12	21 12 01 12	21 12 01 12
Starting Location (Lat., Long., Agl.)	36.146533 N 33.542340 E 100.0 m	36.146533 N 33.542340 E 100.0 m	36.146533 N 33.542340 E 100.0 m	36.146533 N 33.542340 E 100.0 m	36.146533 N 33.542340 E 100.0 m	36.146533 N 33.542340 E 100.0 m
Total Run Time (hrs)	72	72	72	72	72	72
Direction	Forward	Forward	Forward	Forward	Forward	Forward
Top of Model (m)	100000	100000	100000	100000	100000	100000
Vertical Motion Method	Input model data	Input model data	Input model data	Input model data	Input model data	Input model data
Set up Meteorological Data Files	gdas1.feb21.w2	gdas1.feb21.w2	gdas1.may21.w3	gdas1.may21.w3	gdas1.dec21.w1	gdas1.dec21.w1
Hours of Emission (hrs)	48	48	48	48	48	48
Release Start (yy mm dd hh min)	21 02 08 12 00	21 02 08 12 00	21 05 15 12 00	21 05 15 12 00	21 12 01 12 00	21 12 01 12 00
Center (Lat., Long.)	0 0	0 0	0 0	0 0	0 0	0 0
Spacing (Lat., Long.)	0.05	0.05	0.05	0.05	0.05	0.05
Span (Lat., Long.)	10 10	10 10	10 10	10 10	10 10	10 10
Number of Vertical Levels	1	1	1	1	1	1
Height of the Levels (m)	500	500	500	500	500	500
Interval (hrs)	00 04 00	00 04 00	00 04 00	00 04 00	00 04 00	00 04 00
Particle Diameter, Density, Shape	1 1 1	0 0 0	1 1 1	0 0 0	1 1 1	0 0 0
Velocity (m/s), MWt (g), A-ratio, D-ratio, Henry	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0	0 0 0 0
Henry's (M/a), In-cloud (l/s), Below-cloud (1/s)	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0	0 0 0
Resuspension factor (1/m)	0	0	0	0	0	0
Source Term (Bq)	1.80E+17	1.26E+18	1.80E+17	1.26E+18	1.80E+17	1.26E+18
Dose Conversion Factor (Sv Bq-1 s-1 m3)	3.89E-16	1.69E-14	3.89E-16	1.69E-14	3.89E-16	1.69E-14
Rad. Half-Life (sec)	9,52093E+13	6,94656E+10	9,52093E+13	6,94656E+10	9,52093E+13	6,94656E+10

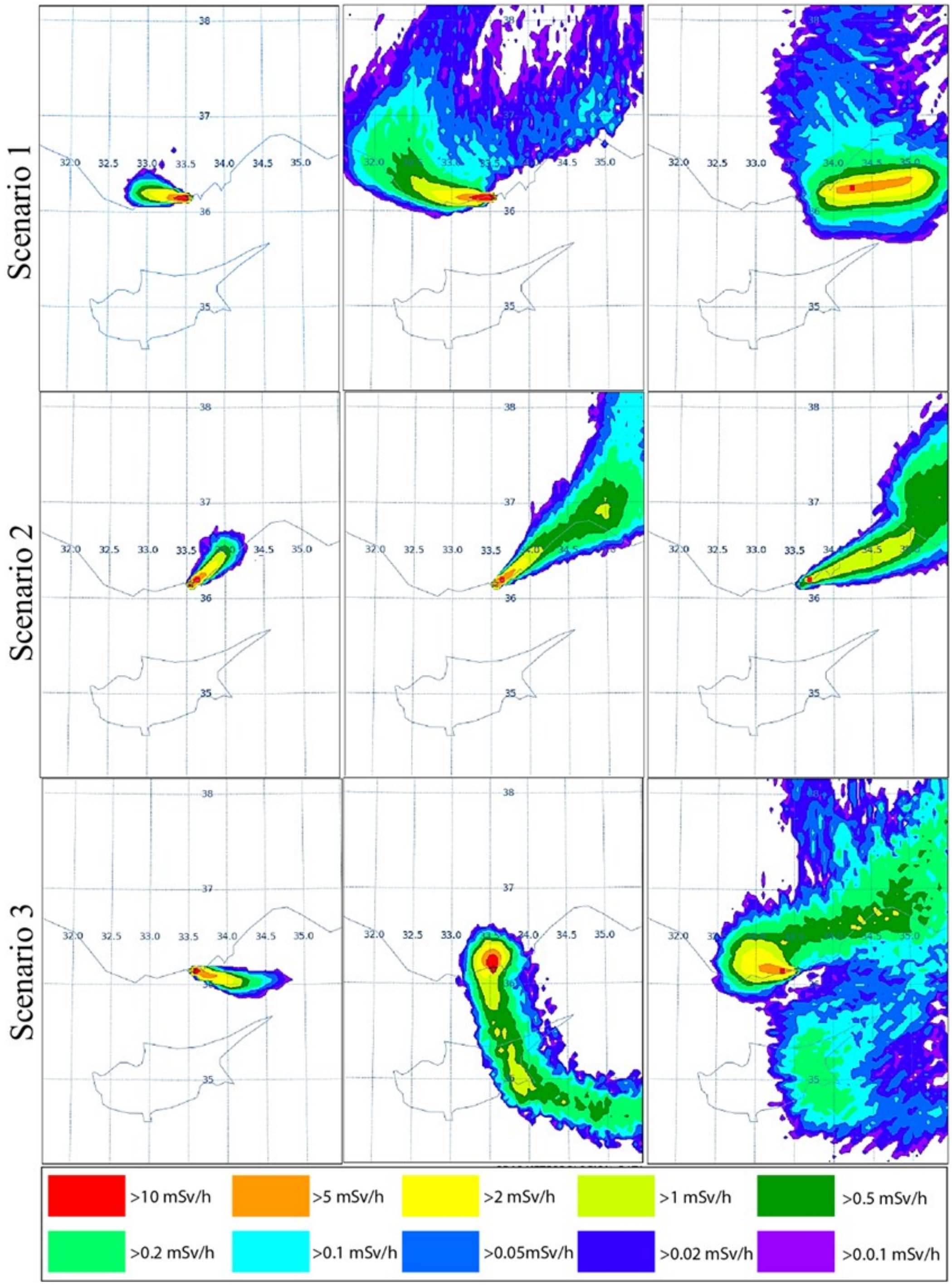

Figure 4.9. Atmospheric dispersion models of scenarios: the first 4-hours of day 1, 2 and 3

4.6 Nuclear Hazard Mapping for the Akkuyu-NPP

This research mainly focuses on preparing the nuclear hazard maps to determine the evacuation zones providing the initial steps of evacuation planning for Akkuyu-NPP. Within the scope of the nuclear hazard mapping process, at first, the hypothetical accident scenario and the source term for the VVER-1200 type reactor with 3200 MW thermal power are obtained from the work of Fairuz and Sahadath (2020), considering the simulation-based approach, and the dose conversion factors are obtained from FGR-15 (See Appendix A) for Cs-137 and I-131. Then, three scenarios are identified for three different meteorological conditions prevailing around the Akkuyu NPP reactor site. The weekly GDAS data with 1° x 1° grid resolution belonging to 2021 is used to perform the sensitivity analysis and the actual atmospheric dispersion models in HySPLIT. The scenarios are mainly determined considering both the wind speed and the directions in a combined manner. More specifically, this research selects three different wind speeds (low, average, and high), which are selected from the three different periods of 2021. The low-speed wind blows to the west direction, the average-speed wind blows to the east, and the high-speed wind blows to the east and west directions. Since the turbulence factor and the vertical pressure levels of the wind affected the plume direction, 52 weeks of the year 2021 are simulated by HySPLIT to observe the highest ambient dose distribution through the inland. Then, the corresponding week of the month with the lowest (1.9 m/s), the average (5.1 m/s), and the highest (16.3 m/s) wind speed blowing to the inland are selected to be the simulation period in actual simulations: 08-11 February 2021, 15-18 May 2021 and 01-04 December 2021, respectively.

To sum up, the development of the accident scenario, obtaining source term and dose conversion factor, identifying the meteorological conditions, and modeling the atmospheric dispersion present the nuclear hazard mapping preparation process for Akkuyu-NPP. The atmospheric dispersion models of three different periods are superposed in the GIS platform and obtained three nuclear hazard maps to identify the evacuation zones. Overall hazard maps provide radiation exposure zones with varying ambient dose rates (See Figure 4.10.).

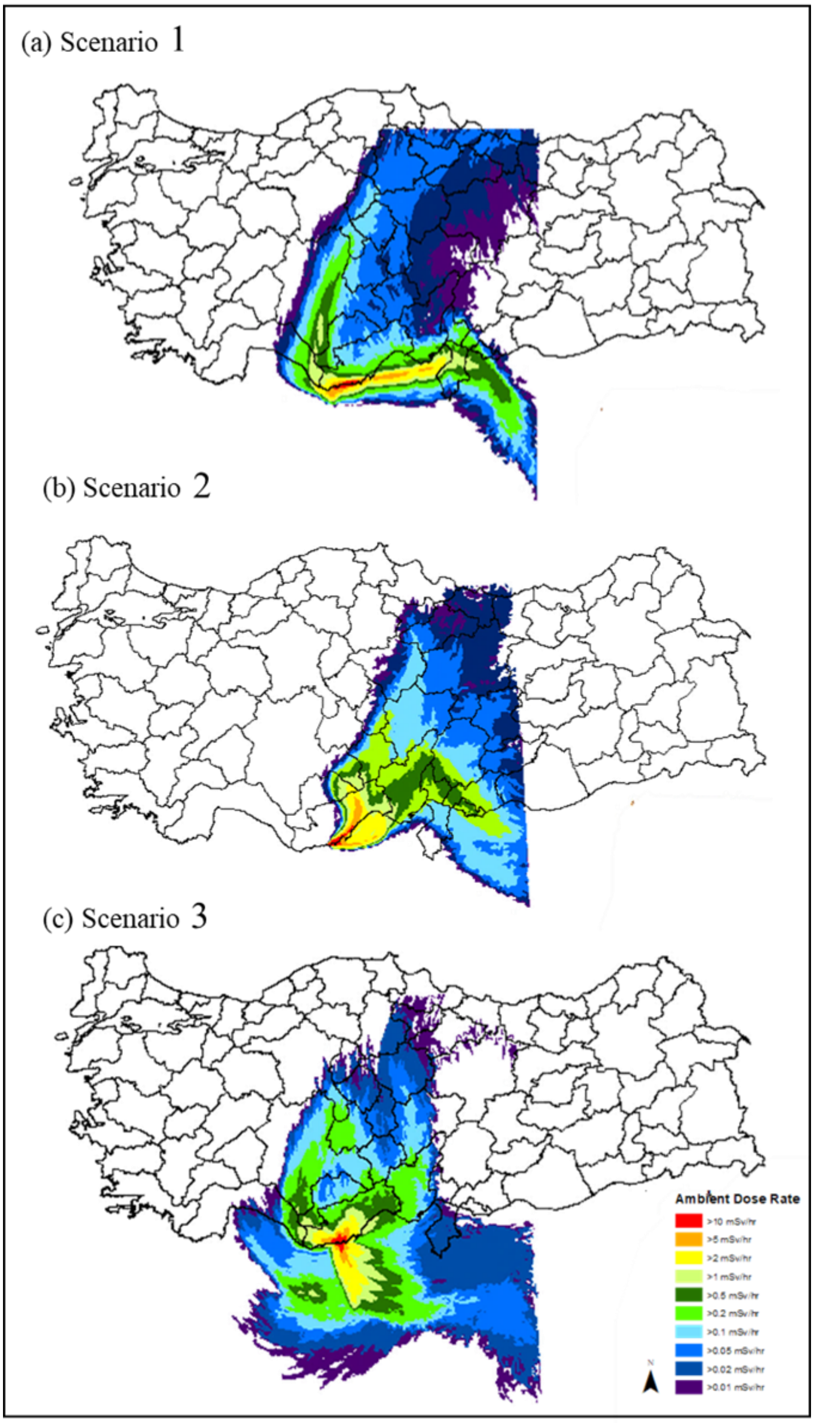

Figure 4.10. Superposed hazard maps displaying overall ambient dose rate distribution integrated from scenario 1, 2 and 3.

4.7 Initial Steps of Evacuation Planning for the Akkuyu-NPP

As the following step of nuclear hazard mapping, this research examines the evacuation zones. From the overall nuclear hazard maps, the zones with a dose rate larger than or equal to 1 mSv/h and 0.5 mSv/h are extracted using ArcMap's 'Select by attributes' tool. The extracted zones are overlapped on a daily basis in a temporal form and obtained daily superposed hazard maps for each scenario to detect the total exposure time (See Figure 4.11. (a)). The radiation hazards zones are grouped according to the total exposure time using the 'Identity feature' tool, and the thematic maps indicating the radiation exposure risk zones are created (See Figure 4.11. (b)). The risk zones are classified as ‘low, medium, and high risk’ within the evacuation zone with a larger than or equal to 1 mSv/h ambient dose rate, and the zones beyond the evacuation zone with smaller than 1 mSv/h and larger than or equal to 0.5 mSv/h ambient dose rate are defined as ‘potential risk zone.’ ‘Low-risk zone’ indicates the areas with a total exposure time of 4- and 8 hours. ‘Medium-risk zone’ displays the areas with 12- and 16 hours of total exposure time. Finally, the ‘high-risk zone’ highlights the areas with 20- and 24 hours of total exposure time. For the ‘potential risk zone,’ this research overlaps the 24-hours results, which is smaller than 1 mSv/h and larger than or equal to 0.5 mSv/h ambient dose rate, and creates the zone using outside borders. This research considers this zone to indicate that evacuation preparation may be implemented in this zone as well since the radioactive plume may expand. All the maps within this research are prepared using the available GIS-based vector data of Mersin Province, including the districts and neighborhoods obtained from Mersin Metropolitan Municipality. The maps are prepared in the coordinate system WGS 1984 UTM ZONE 36N, and the grid sizes can differ depending on the maps. Subsequently, the radiation exposure risk zones are examined at the neighborhood level using the 'Select by location tool. The neighborhoods are classified according to whether they are within the risk zones or where the boundary of risk zones passes through (See Figure 4.11. (c)), and the affected area size is calculated by using the 'Calculate geometry' tool. In this way, the vulnerability level is observed at the neighborhood level. Afterward, demographic data within Mersin province is defined as an attribute to the neighborhoods in the risk zones to estimate the evacuation demand, and thematic maps are generated to observe the spatial distribution of the affected population (See Figure 4.11. (d)).

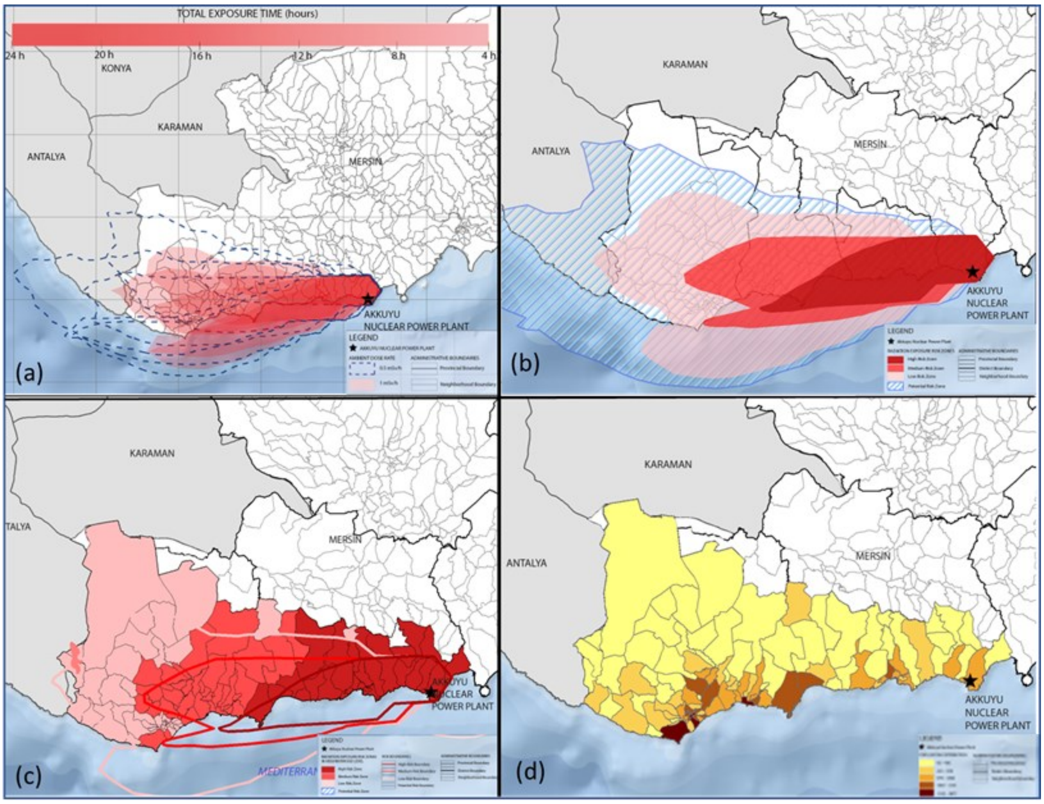

Figure 4.11. Example of hazard mapping process.

CHAPTER 5

EVACUATION PLANNING FOR THE AKKUYU-NPP

This research studies the atmospheric dispersion of radioactive plume from a predefined hypothetical accident scenario in Akkuyu-NPP to identify the evacuation zones and presents the results in this section. It simulates the radioactive plume based on the three different meteorological scenarios defined in Section 4.4. It analyzes the total affected area and population for each scenario with risk classification based on total exposure time.

5.1 Results on Daily Overlay: Scenario 1

In scenario 1, this research simulates the dispersion of cumulative release of Cs-137 and I-131 from a hypothetical accident in the Akkuyu Nuclear Power Plant between 08 February and 11 February 2021. It considers only the radioactive plume with the ambient dose rate higher than or equal to 1 mSv/h and higher than or equal to 0.5 mSv/h for the evacuation zoning. As a result, the research maps the overlapped dispersion models with a 4-hour time interval on a daily basis and obtains three hazard maps for scenario 1 to analyze the affected areas within Turkey. The superposed hazard maps can be interpreted as follows:

- The map shows the total radiation exposure time within the evacuation zone with the gradient red-color
- The reddest color shows the highest exposure time
- From the reddest to the less red color, the map shows that the total exposure time decreases

- The dashed lines show the possible evacuation zone, which means that the radioactive plume may expand to this border, and this zone may require evacuation preparation.
- The following outer dashed lines show the safe zone. Therefore, it is possible to evacuate people to the outer boundary of the dashed lines.

The first day observations indicate that the radioactive plume starts to disperse through the west-northwest direction, then fluctuates to the west and west-southwest directions from Akkuyu Nuclear Power Plant. Overall, the atmospheric dispersion of the radioactive plume follows a relatively concentric pattern on the first day of observations (See Figure 5.1).

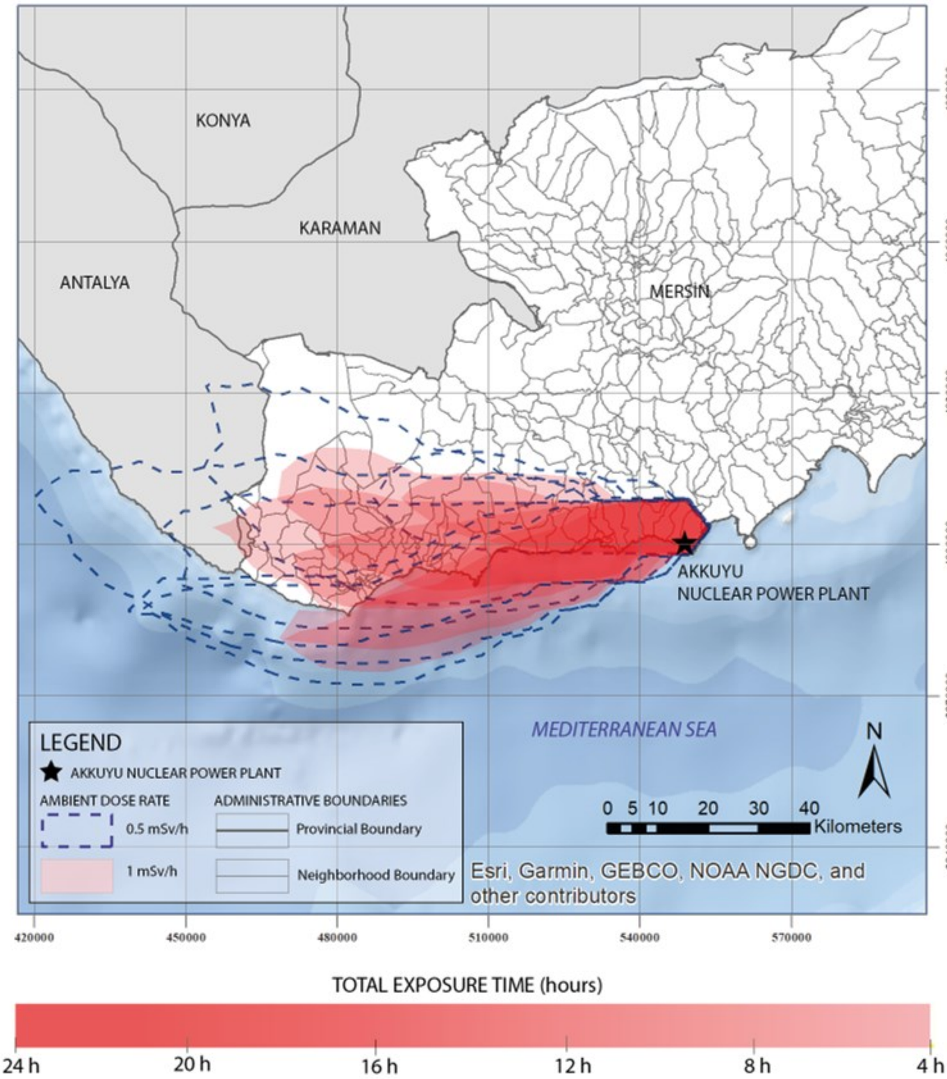

Figure 5.1. Superposed nuclear hazard map displaying total exposure time for Akkuyu Nuclear Power Plant: Scenario 1 day 1 (From 12.00 pm 08 February 2021 to 09 February 2021) (Grid size: 30x30 km)

The risk classification map separates the radiation exposure zone into four zones, three of them are within the evacuation zone, and the other one is beyond the evacuation zone. The dark-red color shows the high-risk zone, the lighter-red color shows the medium-risk zone, and the pinkish color shows the low-risk zone. The blue-hatched area beyond the evacuation zone shows the potential risk zone. According to the risk classification map for scenario 1 day 1 (See Figure 5.2), the radiation exposure risk zones present a relatively linear pattern accumulated to the west side of the Akkuyu Nuclear Power Plant.

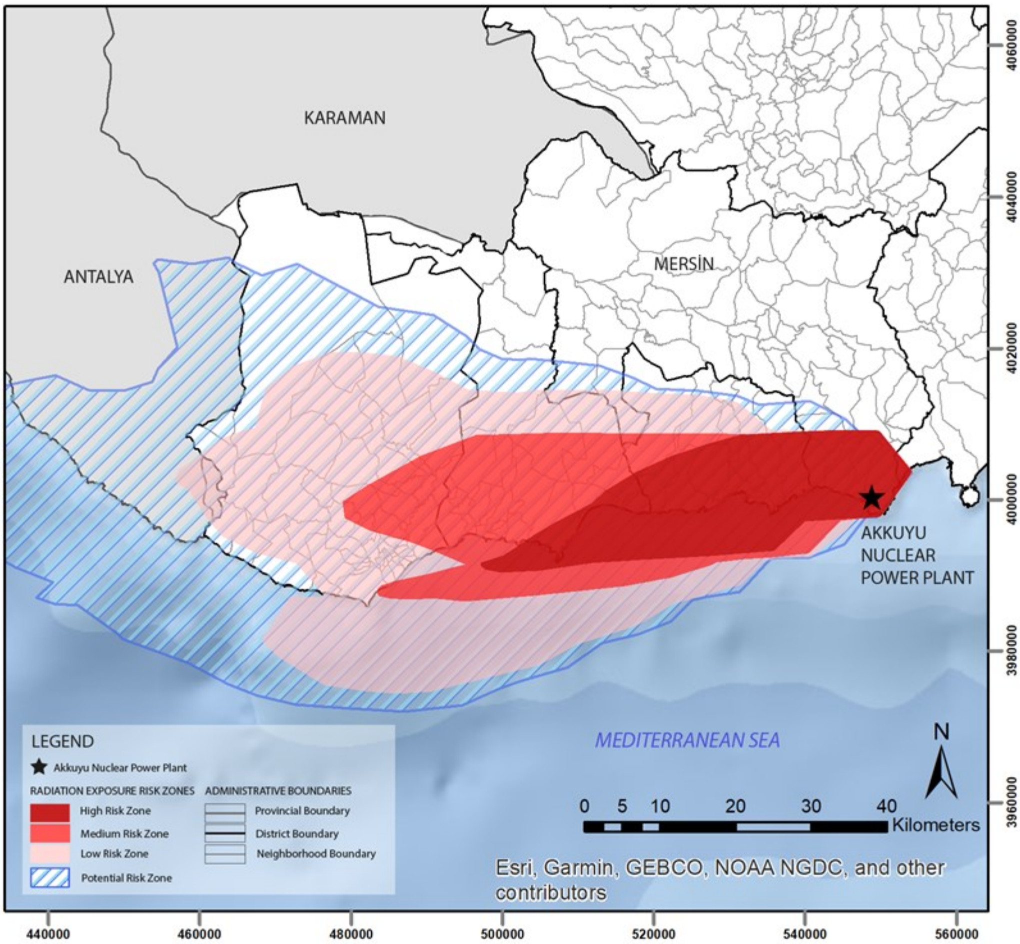

Figure 5.2. Radiation exposure risk classification map for Akkuyu Nuclear Power Plant: Scenario 1 Day 1 (From 12.00 pm 08 February 2021 to 09 February 2021) (Grid size: 20x20 km)

This research determines the evacuation planning zones at the neighborhood level. In other words, it classifies the neighborhoods according to the risk zones determined through the daily overlapped dispersion maps. This way, it is possible to identify the neighborhoods with high, medium, low, and potential risks.

This research maps the radiation exposure risk zones at the neighborhood level, classifying them according to whether they are within the risk zones or where the boundary of risk zones passes through (See Figure 5.3). The map shows the reference borders of predefined risk zones in neighborhoods. The neighborhoods with the bordeaux-red, red, and pinkish color indicate the high-risk, medium-risk, and low-risk zones, respectively. Moreover, the blue-hatched neighborhood displays the potential risk zone.

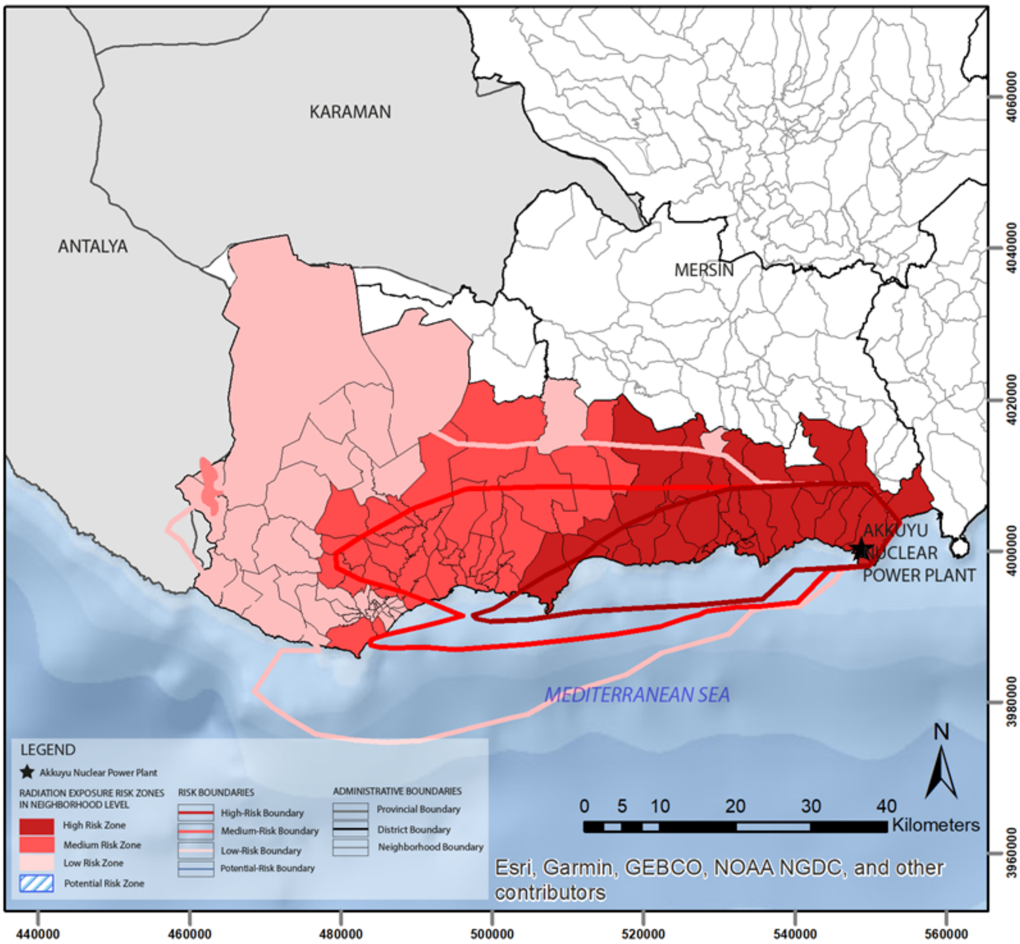

Figure 5.3. Radiation exposure risk classification map at the neighborhood level: Scenario 1 day 1 (From 12.00 pm 08 February 2021 to 09 February 2021) (Grid size: 20x20 km)

From the map indicating the radiation exposure risk classification at the neighborhood level, the area size covering the risk zones is calculated by ArcMap’s calculate geometry tool. Then, the percentages of the areas over the total area are calculated and shown in Table 5.1.

Table 5.1 *Area of radiation exposure risk classes: Scenario 1 day 1 (From 12.00 pm 08 February 2021 to 09 February 2021)*

Radiation Exposure Risk Zones	Area (sq. km)	Percentage (%)
Potential Risk Zone	15,9	0,6
Low Risk Zone	1200,7	46,4
Medium Risk Zone	719,9	27,8
High Risk Zone	653,3	25,2
TOTAL	2589,8	100,0

Table 5.1 shows that the 653.3 sq. km of the north-western part of the Akkuyu Nuclear Power Plant is under high nuclear exposure risk. This area covers 25.2% of the evacuation zone defined on the first day of scenario 1. Areas within the medium risk cover 719.9 sq. km following the high-risk zone. In other words, 27,8% of the evacuation zone is under the medium radiation exposure risk. The areas with a low risk of radiation exposure cover 1200.7 sq. km following the medium-risk zone, which covers most of the evacuation zone with 46.4%. The potential risk zone on the first day of scenario 1 situates on a 15.9 sq. km area with %0.6 of the total area.

The research further analyses the affected population situated under the classified radiation exposure at the neighborhood level. Within the scope of this consideration, the population distribution is mapped and shown in Figure 5.4.

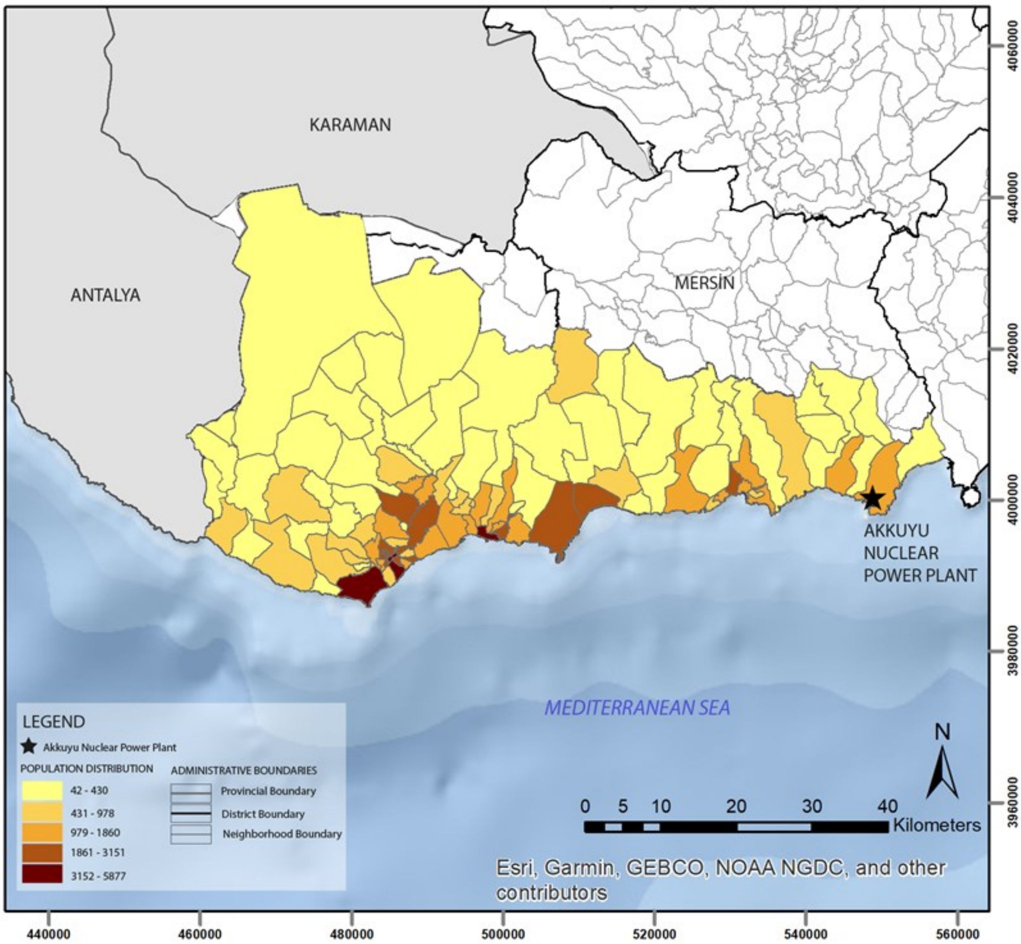

Figure 5.4. Population distribution map on radiation exposure risk zones: Scenario 1 day 1 (From 12.00 pm 08 February 2021 to 09 February 2021) (Grid size: 20x20 km)

This map includes the Mersin population attributes in 2021 provided by TURKSTAT and identifies the total population within the risk zones at the neighborhood level. Furthermore, the quantitative chart is created to compare the population distribution in the risk zones and shown in Figure 5.5.

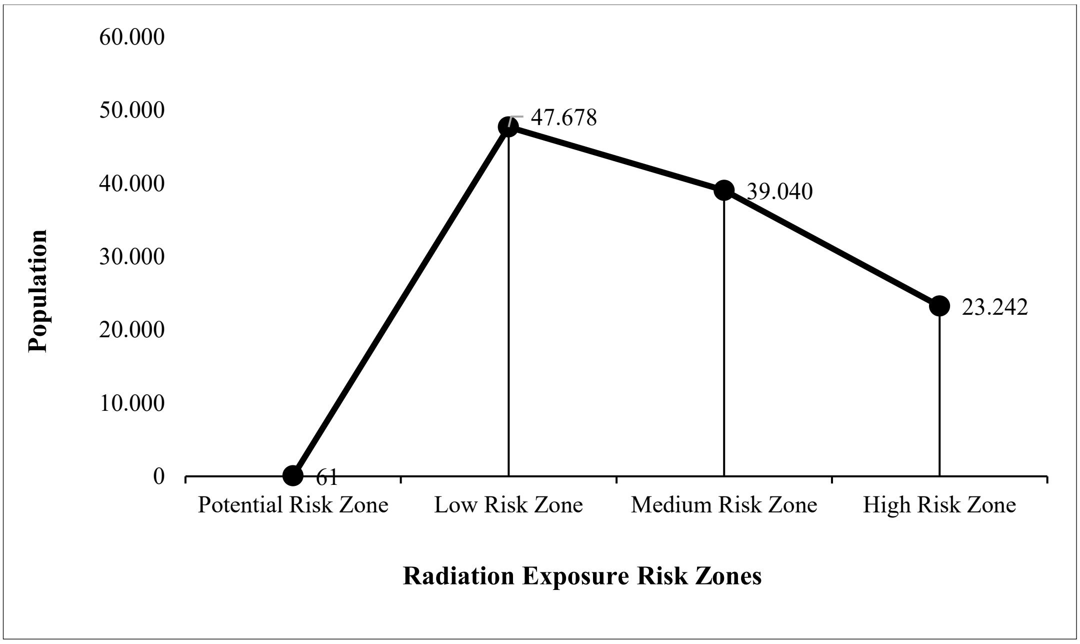

Figure 5.5. Quantitative chart displaying total population distribution on radiation exposure risk zones: Scenario 1 day 1 (From 12.00 pm 08 February 2021 to 09 February 2021)

According to the chart, the results show that 110,021 persons situate under the radioactive plume, which is the total evacuation demand of scenario 1, day 1. The high-risk zone includes 21.1% of the total population with 23,242 persons, and the medium-risk zone comprises 35.5% of the total population with 39,040. The low-risk zone includes the largest population, with 47,678 comparing the other zones, and covers 43.3% of the total population within the evacuation zone. Furthermore, the potential risk zone covers only 0.1% of the total population, with 61 persons.

The atmospheric dispersion results on the second day of scenario 1 are mapped and shown in Figure 5.6. In the first 12 hours of the second day, the radioactive plume moves over the path, similar to the first day; however, it starts to expand through the West and West-Southwest directions. After 12 hours, the direction of the radioactive plume changes to the North direction and disperses outside the provincial borders of Mersin for the first time. In the last four hours of the second day, the radioactive plume changes its direction dramatically and starts to move in the East direction.

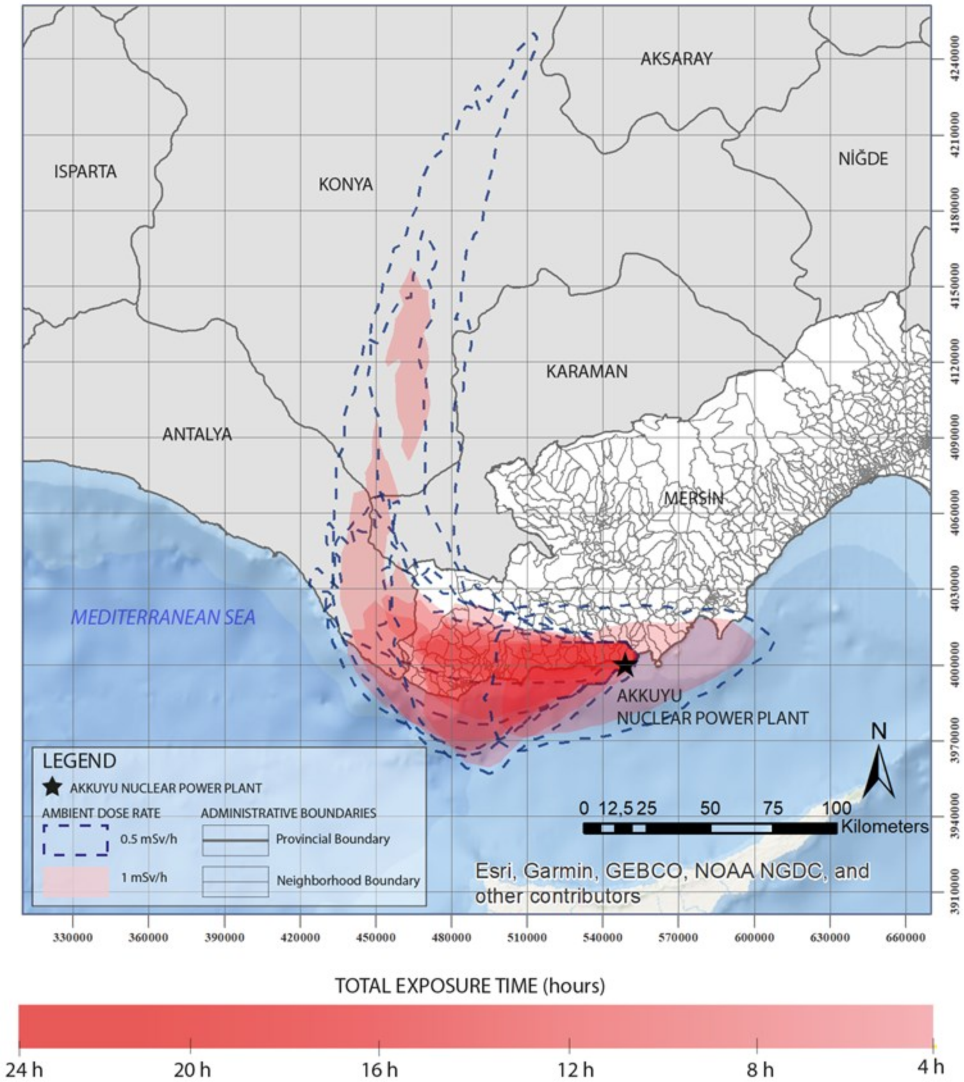

Figure 5.6. Superposed nuclear hazard map displaying total exposure time for Akkuyu Nuclear Power Plant: Scenario 1 day 2 (From 12.00 pm 09 February 2021 to 10 February 2021) (Grid size: 30x30 km)

The risk classification map by total exposure time for the second day of scenario 1 is shown in Figure 5.7. From the map displaying risk classification for the second day of scenario 1, it is identified that the high and medium risk zones expand in the same direction as the first day while the low and potential risk zones expand both in the North and East direction.

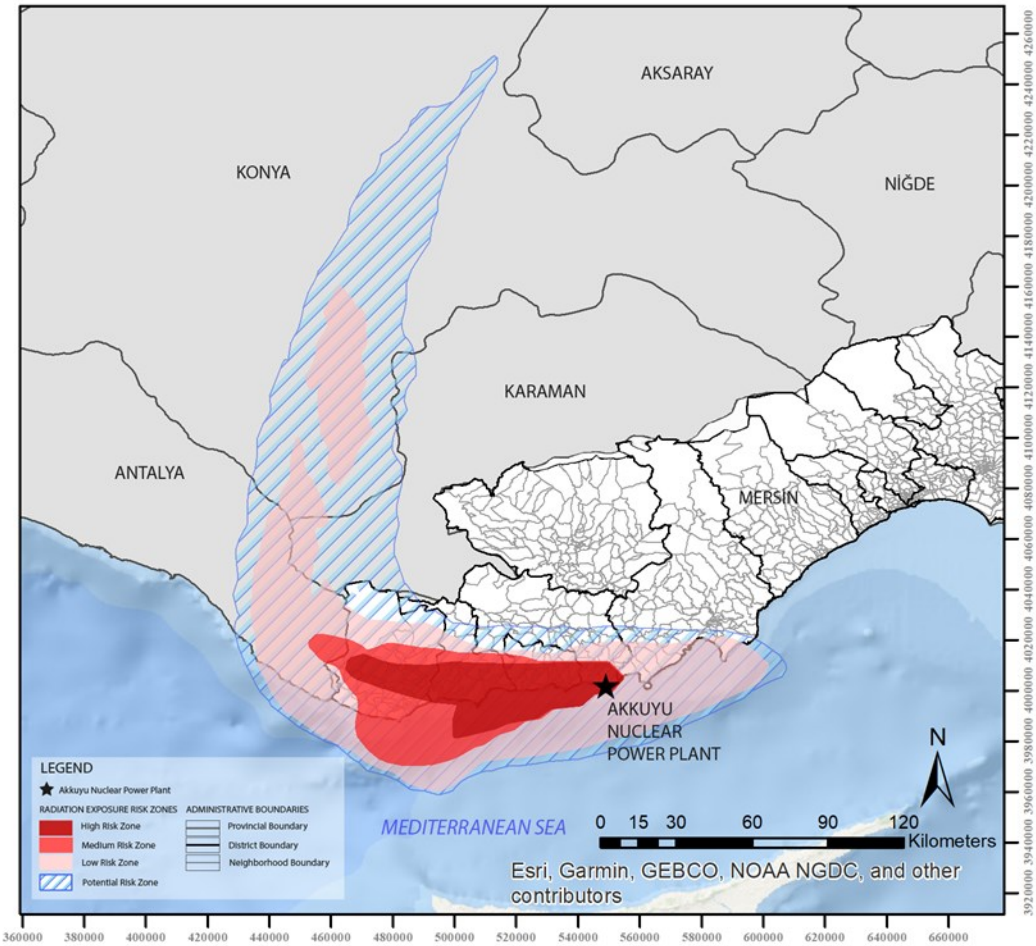

Figure 5.7. Radiation exposure risk classification map for Akkuyu Nuclear Power Plant: Scenario 1 day 2 (From 12.00 pm 09 February 2021 to 10 February 2021) (Grid size: 20x20 km)

Further risk classification analysis is made at the neighborhood level, and the map is shown in Figure 5.8. The map prepared for analyzing radiation exposure risk classification at the neighborhood level for the second day of scenario 1 provides the total affected area size by the risk zones. Then, the area sizes by risk zones are identified and shown in Table 5.2.

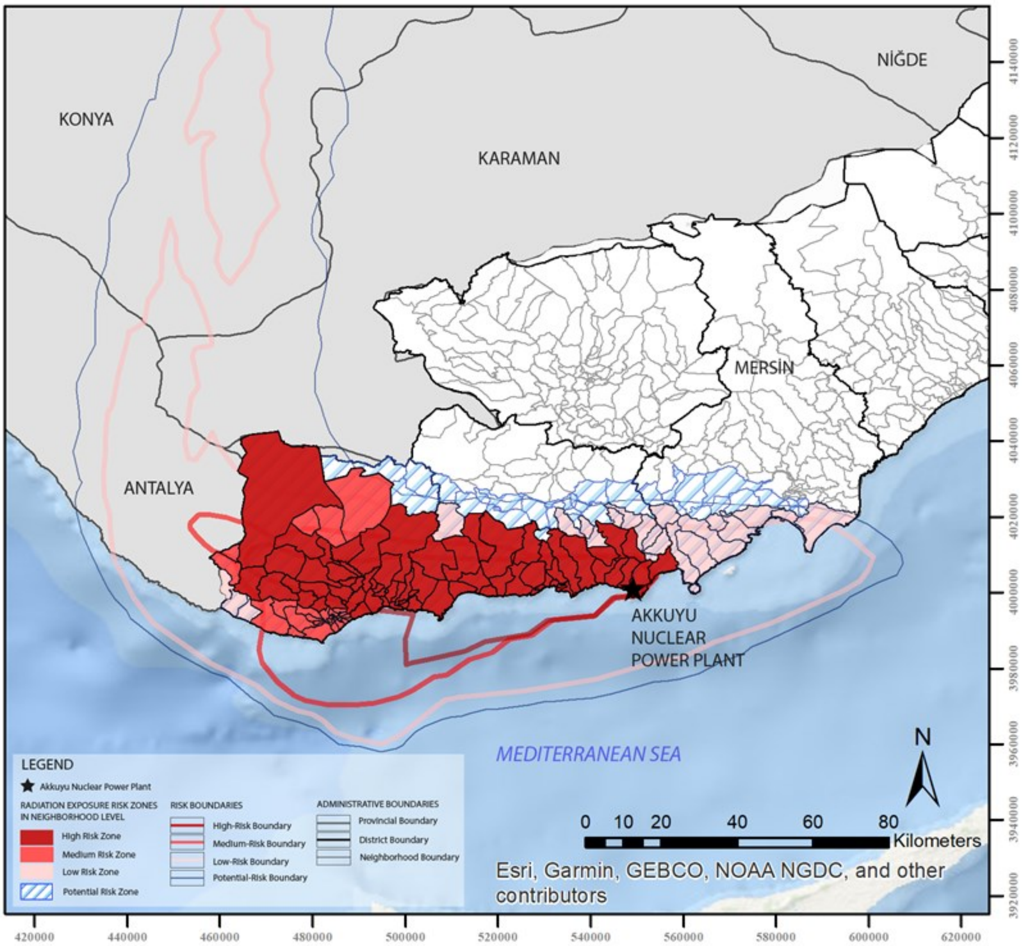

Figure 5.8. Radiation exposure risk classification map at the neighborhood level: Scenario 1 day 2 (From 12.00 pm 09 February 2021 to 10 February 2021) (Grid size: 20x20 km)

Table 5.2 *Area of radiation exposure risk classes: Scenario 1 day 2 (From 12.00 pm 09 February 2021 to 10 February 2021)*

Radiation Exposure Risk Zones	Area (sq. km)	Percentage (%)
Potential Risk Zone	771,8	20,0
Low Risk Zone	603,9	15,7
Medium Risk Zone	438,0	11,4
High Risk Zone	2038,3	52,9
TOTAL	3852,0	100,0

According to Table 5.2, it is identified that areas within the high risk of radiation exposure cover most of the affected area, with 2038,3 sq. km corresponding to 52,9% of the total. The medium-risk zone covers 438 sq. km following the high-risk zone and corresponds to 11.4% of the total. The areas with a low risk of radiation exposure cover 603.9 sq. km of the northeastern part of Akkuyu Nuclear Power Plant, which is 15,7% of the total evacuation zone. Lastly, it is identified that the potential risk zone covers more than the previous day, with a 771.8 sq. km area size corresponding to 20% of the total zone.

The population distribution map on classified radiation exposure risk zones is prepared to observe the affected population and is shown in Figure 5.9. From the map indicating the population distribution, the total population within the risk classification is identified and compared in the quantitative chart shown in Figure 5.10.

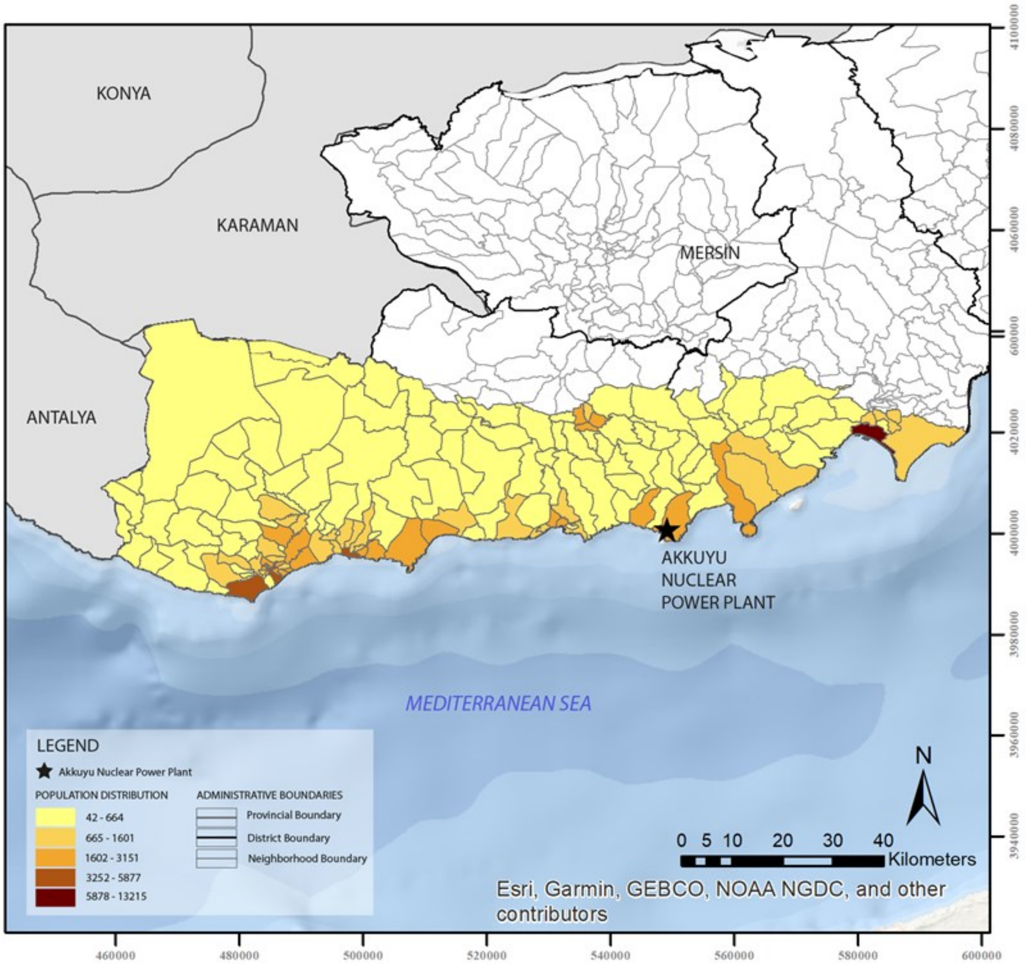

Figure 5.9. Population distribution map on radiation exposure risk zones: Scenario 1 day 2 (From 12.00 pm 09 February 2021 to 10 February 2021) (Grid size: 20x20 km)

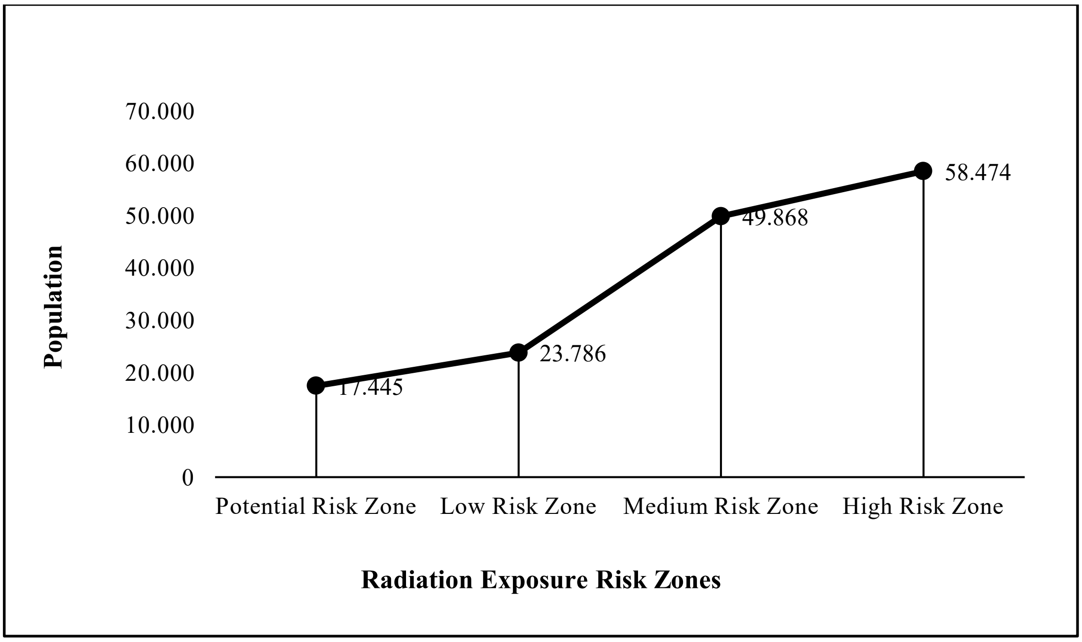

Figure 5.10. Quantitative chart displaying total population distribution on radiation exposure risk zones: Scenario 1 day 2 (From 12.00 pm 09 February 2021 to 10 February 2021)

According to scenario 1, day 2, 149,573 persons situate in radiation exposure zones, which is the total evacuation demand. The results show that the largest population, with 58,474 persons, lives in the high-risk zone, which corresponds to 39.1% of the total population. Despite covering the smallest area, the medium-risk zone consists of 49,868 persons, which is 33.3% of the total population. The low-risk zone includes 15.9% of the total population, with 23,786 persons. The potential-risk zone consists of the smallest population, with 17,445 persons on the second day of scenario 1; however, it shows a dramatic increase compared to day 1.

Since this research considers the emission duration as 48 hours long, the center of the radioactive plume starts to move from the source and slightly gets smaller at the end of the second day. On the last day, observations indicate that the dispersion direction of the radioactive plume turns against the first-day plume and moves over between the direction East-Northeast and East from Akkuyu Nuclear Power Plant (See Figure 5.11).

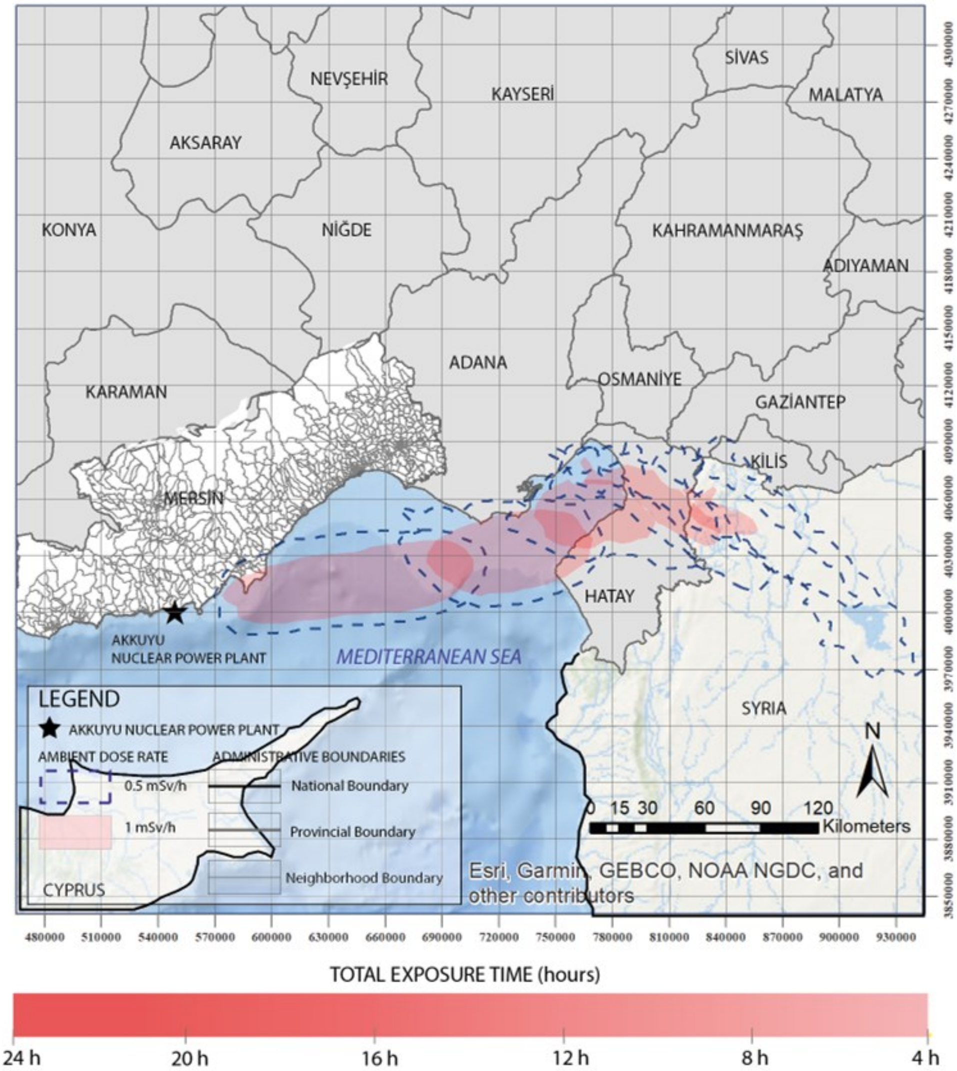

Figure 5.11. Superposed nuclear hazard map displaying total exposure time for Akkuyu Nuclear Power Plant: Scenario 1 day 3 (From 12.00 pm 10 February 2021 to 11 February 2021) (Grid size: 30x30 km)

From the map displaying risk classification for the last day of scenario 1 (See Figure 5.12), it is identified that the total radiation exposure risk diminishes, and only two risk zones are left: the low-risk zone and the potential risk zone. The risk zones change their direction on a relatively opposite side compared to day 1 and day 2 of scenario 1, cross the national boundary of Turkey, and finally reach Syria.

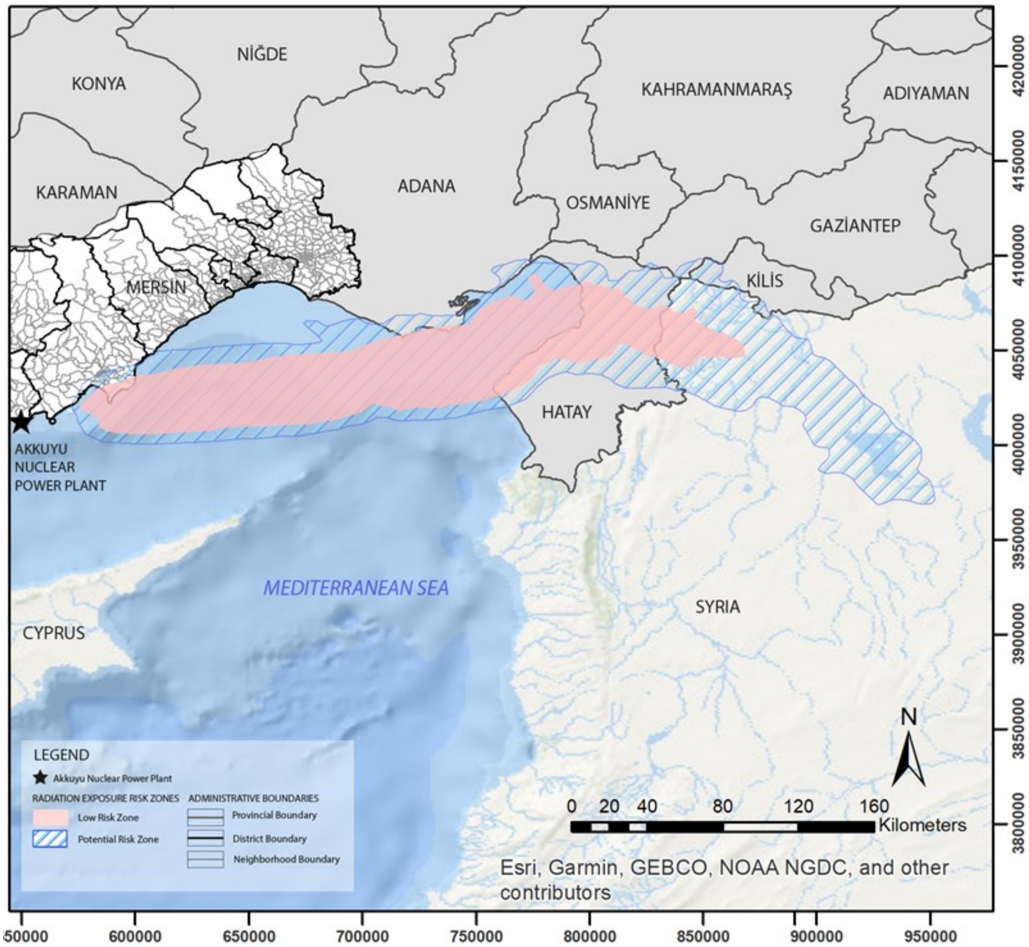

Figure 5.12. Radiation exposure risk classification map for Akkuyu Nuclear Power Plant: Scenario 1 day 3 (From 12.00 pm 10 February 2021 to 11 February 2021) (Grid size: 50x50 km)

The risk classification analysis is made at the neighborhood level, and the map is shown in Figure 5.13. Then, the area sizes within the risk zones are calculated and presented in Table 5.3.

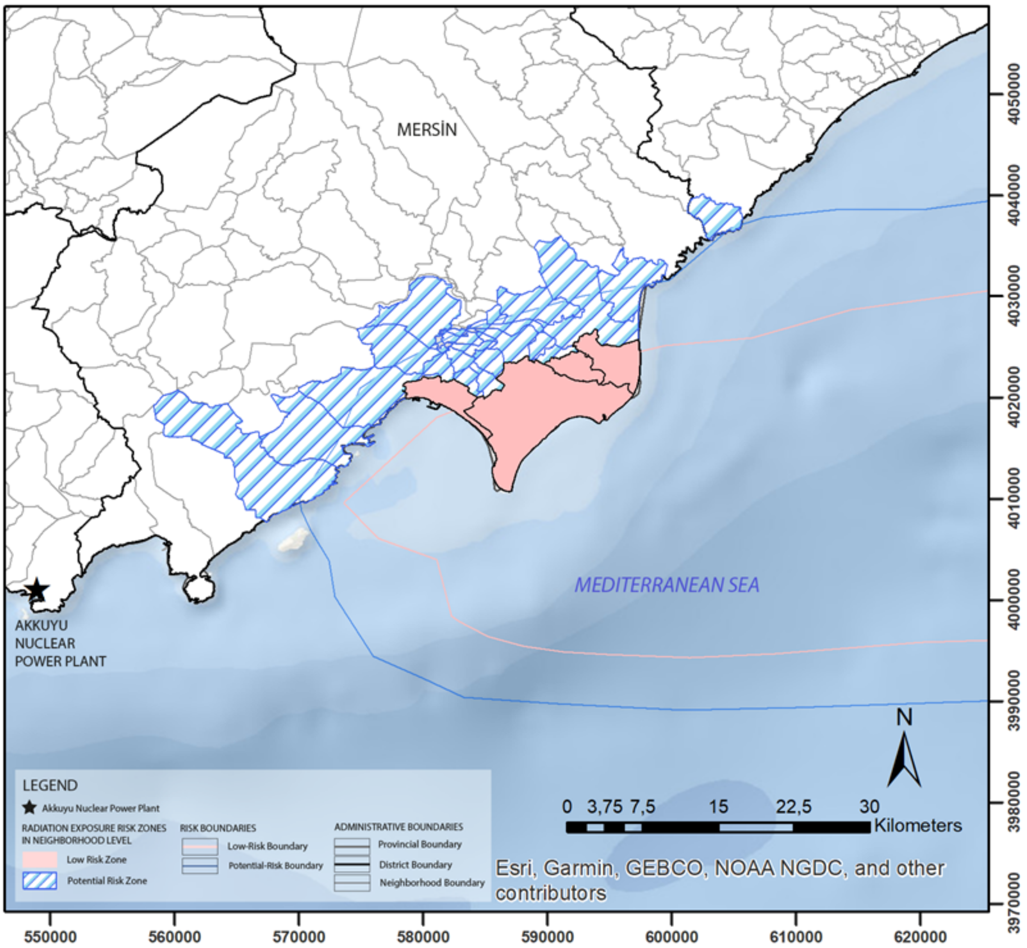

Figure 5.13. Radiation exposure risk classification map at the neighborhood level: Scenario 1 day 3 (From 12.00 pm 10 February 2021 to 11 February 2021) (Grid size: 10x10 km)

Table 5.3 *Area of radiation exposure risk classes: Scenario 1 day 3 (From 12.00 pm 10 February 2021 to 11 February 2021)*

Radiation Exposure Risk Zones	Area (sq. km)	Percentage (%)
Potential Risk Zone	327,8	74,3
Low Risk Zone	113,4	25,7
TOTAL	441,2	100

According to Table 5.3, it is identified that the total affected area size by the radioactive plume dramatically diminishes. Although the low-risk zone covers a small part of the total area with 113.4 sq. km corresponding to 25.7% of the total, 74.3% of the area still bears the potential risk with 327.8 sq. km size.

The population distribution map on classified radiation exposure risk zones is prepared to observe the affected population and is shown in Figure 5.14. From the map indicating the population distribution, the total population within the risk classification is identified and compared in the quantitative chart shown in Figure 5.15.

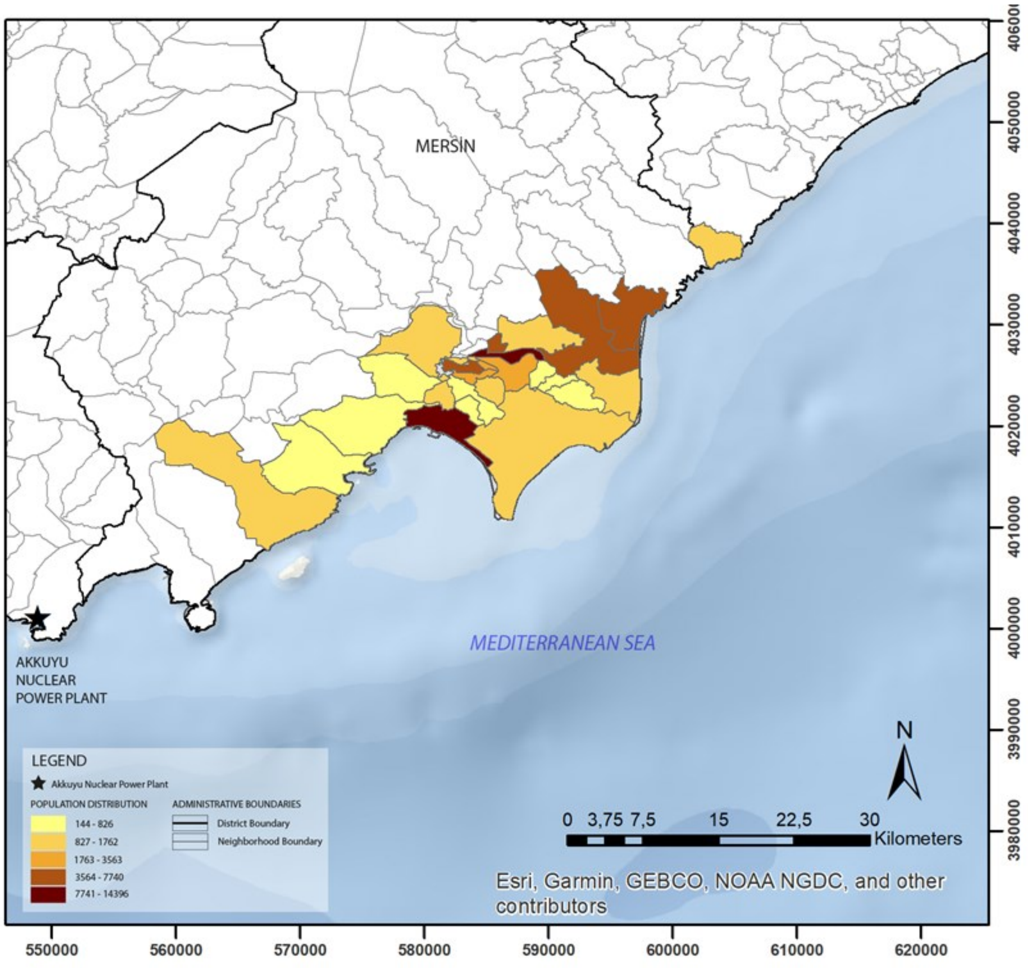

Figure 5.14. Population distribution map on radiation exposure risk zones: Scenario 1 day 3 (From 12.00 pm 10 February 2021 to 11 February 2021) (Grid size: 10x10 km)

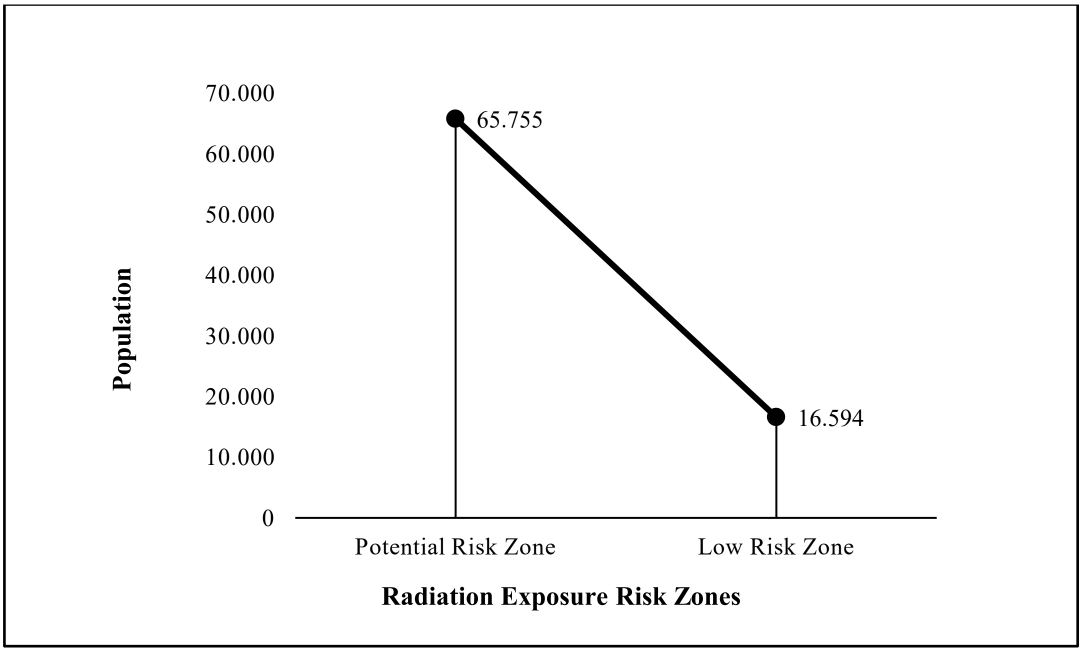

Figure 5.15. Quantitative chart displaying total population distribution on radiation exposure risk zones: Scenario 1 day 3 (From 12.00 pm 10 February 2021 to 11 February 2021)

According to the chart, it is identified that the total population under the low-risk zone is 16,594 persons corresponding to 20.2% of the total population. In comparison, the largest population within day 3 situate in the potential risk zone with 65,755 persons corresponding to 79.8% of the total population. Overall, the total evacuation demand of scenario 1 day 3 is 82,349 persons.

5.2 Results on Daily Overlay: Scenario 2

In scenario 2, this research simulates the dispersion of cumulative release of Cs-137 and I-131 from a hypothetical accident in the Akkuyu Nuclear Power Plant between 15 May and 18 May 2021. The first day's superposed hazard map of scenario 2 shows that the radioactive plume starts to spread in the Northeast direction from Akkuyu Nuclear Power Plant (See Figure 5.16). After 12 hours, the plume changes its direction to the North and crosses the provincial boundary of Mersin for the first time. Then, the plume starts to fluctuate through the North and North-Northeast directions. After 20 hours, the radioactive plume again turns its path in the Northeast direction.

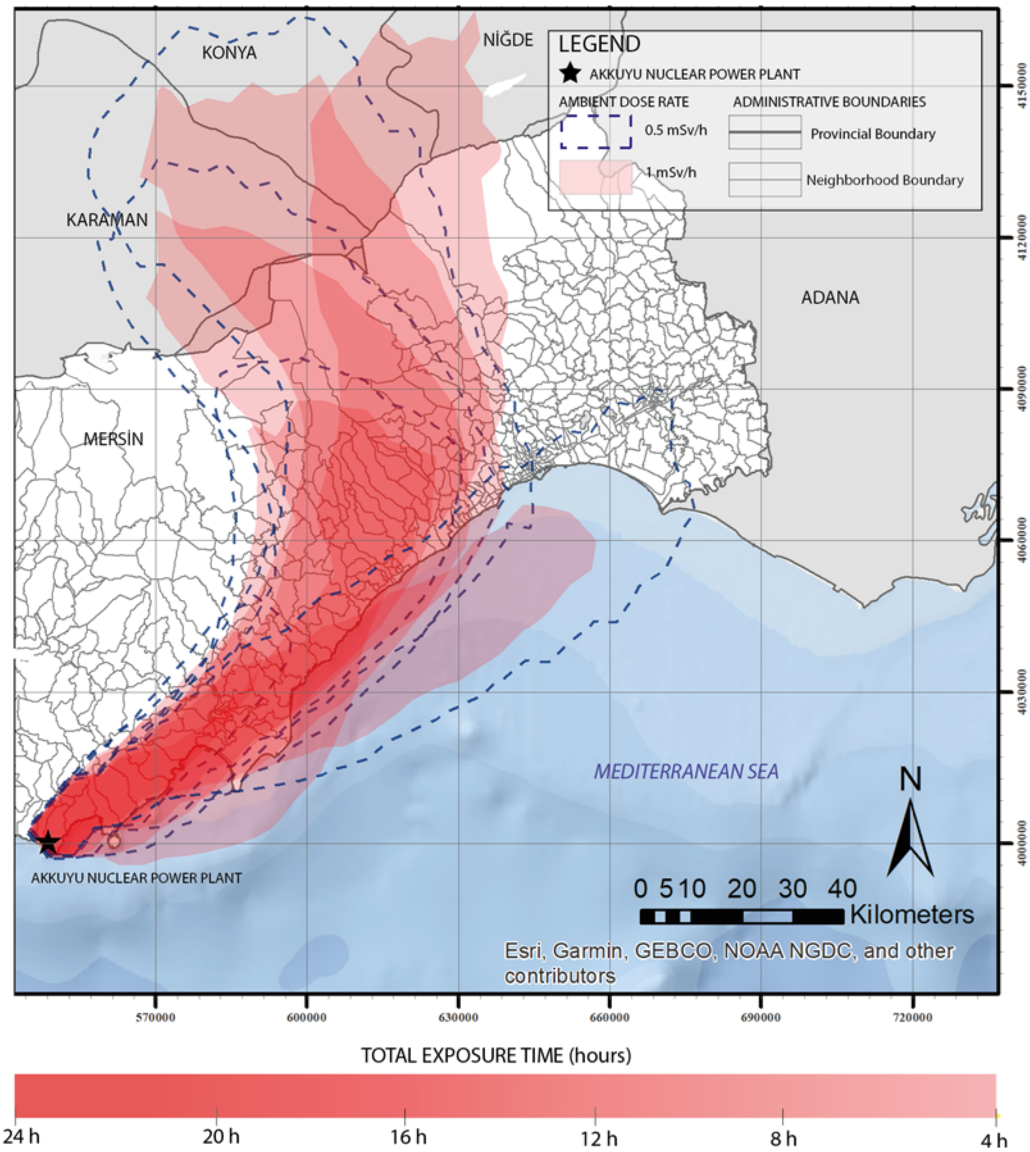

Figure 5.16. Superposed nuclear hazard map displaying total exposure time for Akkuyu Nuclear Power Plant: Scenario 2 day 1 (From 12.00 pm 15 May 2021 to 16 May 2021) (Grid size: 30x30 km)

The risk classification map by total exposure time for the first day of scenario 2 is shown in Figure 5.17. The risk classification map shows that the risk zones present a concentric pattern changing their path from the northeast to the North and crossing the provincial boundary of Mersin with the low and potential risk zones.

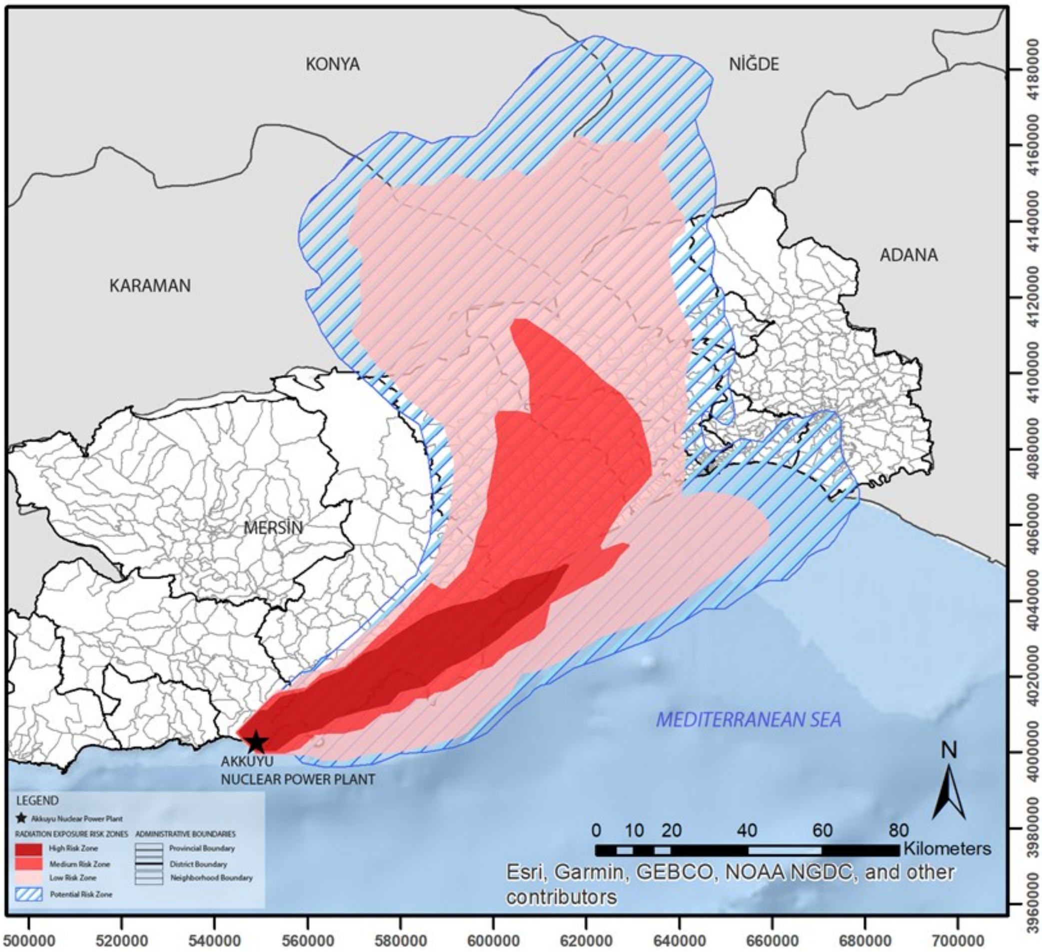

Figure 5.17. Radiation exposure risk classification map for Akkuyu Nuclear Power Plant: Scenario 2 day 1 (From 12.00 pm 15 May 2021 to 16 May 2021) (Grid size: 20x20 km)

Further risk classification analysis is made at the neighborhood level, and the map is shown in Figure 5.18. From the map, the area size of the affected neighborhoods is examined within the boundary of Mersin Province and shown in Table 5.4.

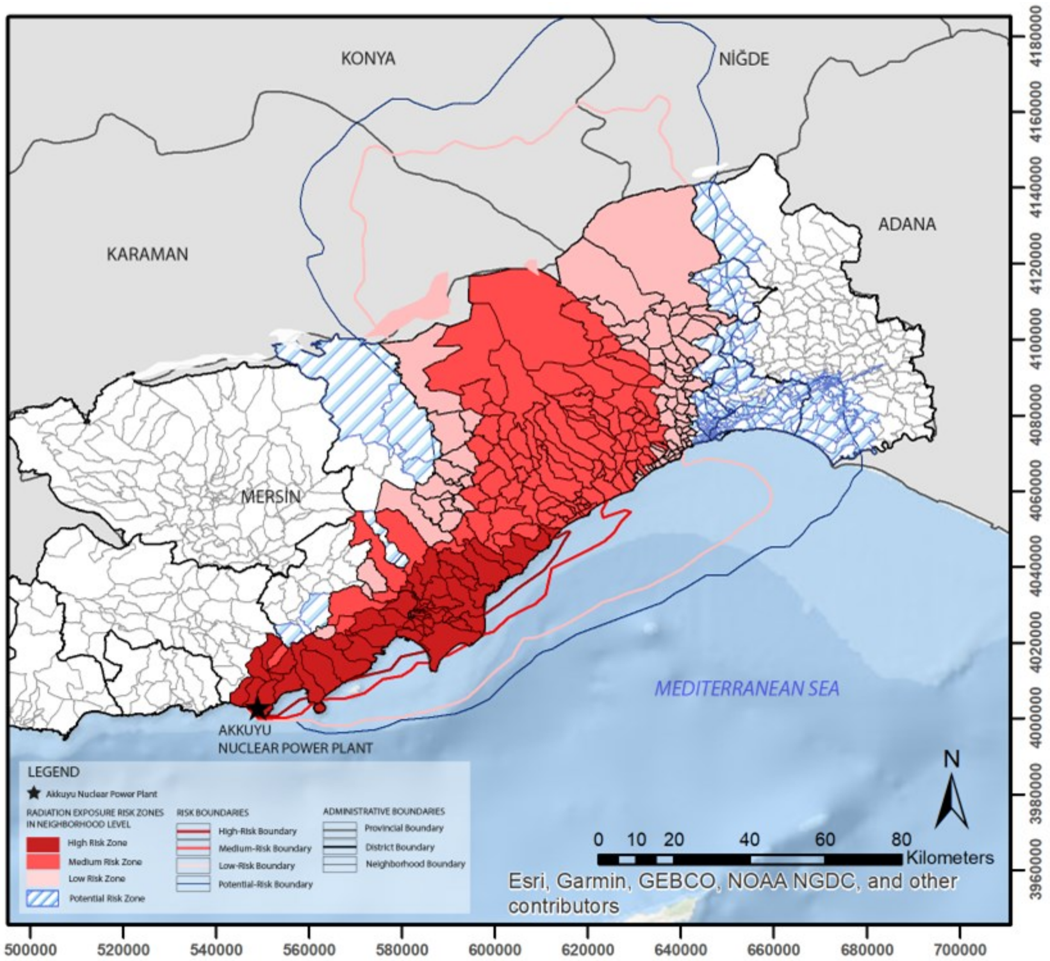

Figure 5.18. Radiation exposure risk classification map at the neighborhood level: Scenario 2 day 1 (From 12.00 pm 15 May 2021 to 16 May 2021) (Grid size: 20x20 km)

Table 5.4 *Area of radiation exposure risk classes: Scenario 1 day 3 (From 12.00 pm 15 May 2021 to 16 May 2021)*

Radiation Exposure Risk Zones	Area (sq. km)	Percentage (%)
Potential Risk Zone	1724,7	23,4
Low Risk Zone	1910,6	25,9
Medium Risk Zone	2697,9	36,6
High Risk Zone	1041,7	14,1
TOTAL	7374,9	100,0

According to Table 5.4, the high-risk zone covers the smallest part of the affected area with 1041.7 sq. km, corresponding to 14.1% of the total. The largest part of the area is under medium risk, with 2697.9 sq. km size corresponding to 36.6% of the total affected area. The neighborhood-level low-risk and potential risk zones have approximately the exact sizes and percentages, namely 1910.6 sq. km (or 25.9% of total) and 1724.7 sq. km (or 23.6% of total), respectively.

The population distribution map on classified radiation exposure risk zones is prepared to observe the affected population and is shown in Figure 5.19. From the map indicating the population distribution, the total population within the risk classification is identified and compared in the quantitative chart shown in Figure 5.20.

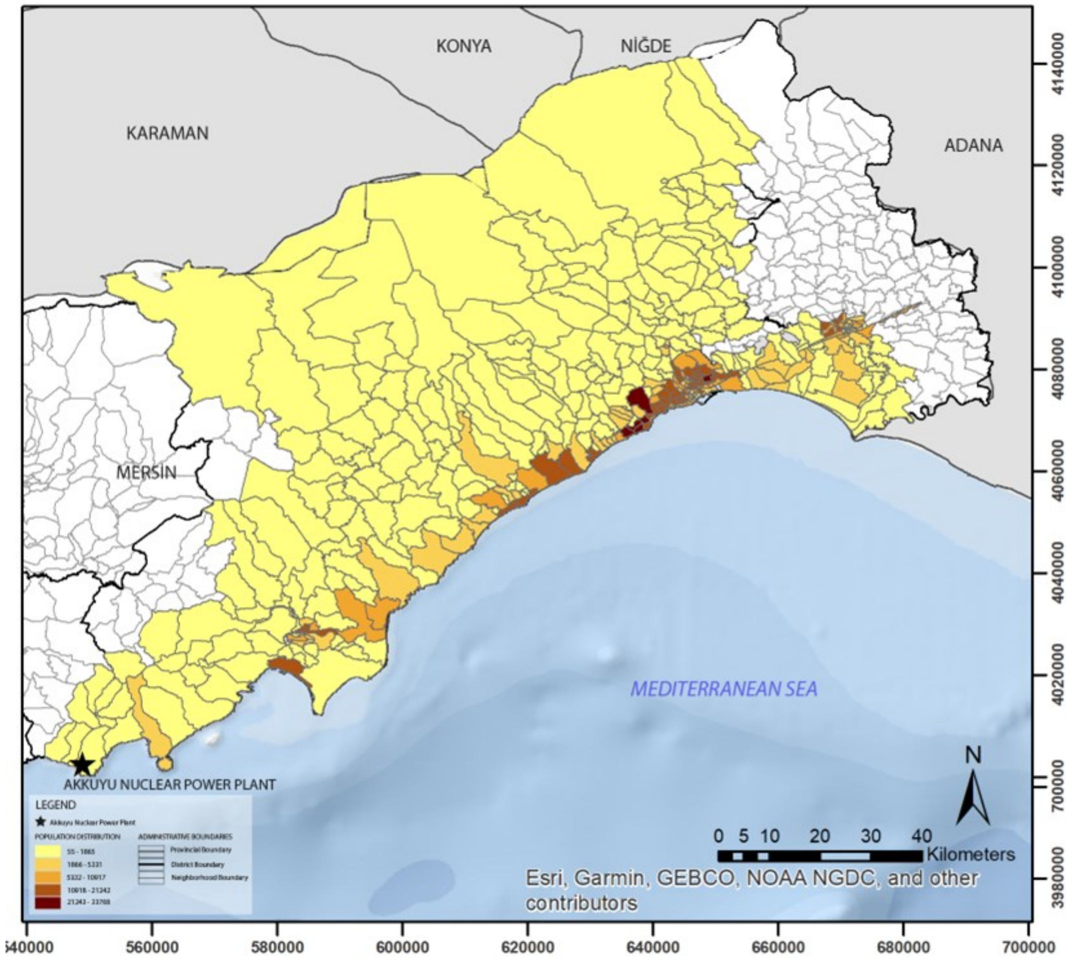

Figure 5.19. Population distribution map on radiation exposure risk zones: Scenario 2 day 1 (From 12.00 pm 15 May 2021 to 16 May 2021) (Grid size: 20x20 km)

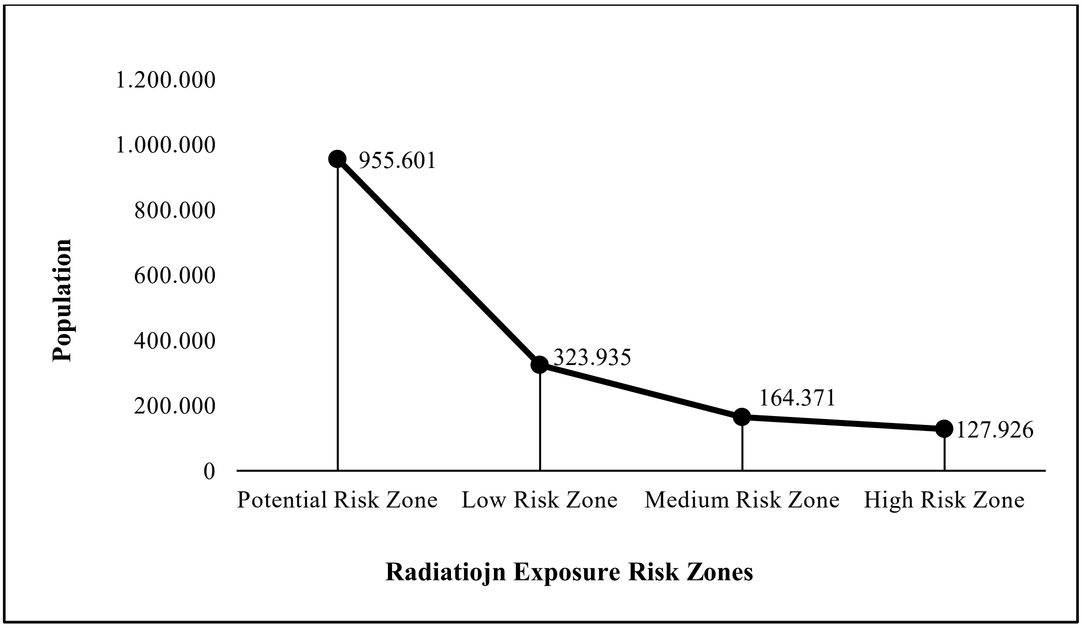

Figure 5.20. Quantitative chart displaying total population distribution on radiation exposure risk zones: Scenario 2 day 1 (From 12.00 pm 15 May 2021 to 16 May 2021)

The quantitative chart of total population distribution in radiation exposure risk zones for the first day of scenario 2 indicates that the high-risk zone has the smallest population, with 127,926 persons corresponding to 8.1% of the total population. The population on medium-risk zone is 164,371 (or 10.5% of total), and the population on low-risk zone is 323,935 (or 20.6% of total). The largest population of the affected area situate under the potential risk zone, with 955,601 persons (or 60.8% of the total). Overall, the total evacuation demand is 1,571,833 persons.

On the second day of observations, the radioactive plume continues dispersing relatively linearly in the Northeast direction (See Figure 5.21). After 16 hours, it starts to fluctuate as an upward curved shape through the North direction, and the largest part stays over the Mediterranean Sea rather than inland.

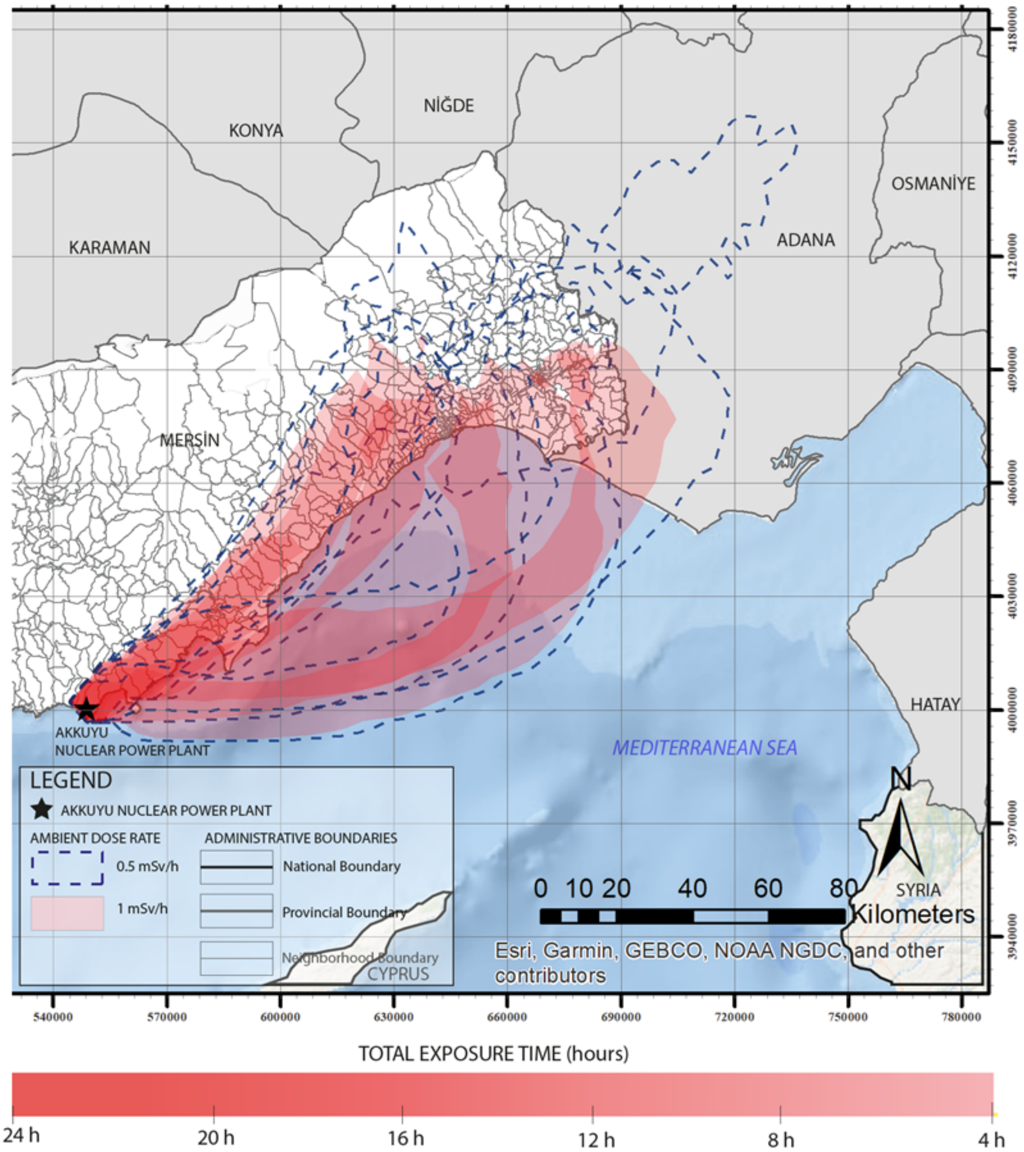

Figure 5.21. Superposed nuclear hazard map displaying total exposure time for Akkuyu Nuclear Power Plant: Scenario 2 day 2 (From 12.00 pm 16 May 2021 to 17 May 2021) (Grid size: 30x30 km)

The risk classification map by total exposure time for the second day of scenario 2 is shown in Figure 5.22. The risk zones present a relatively linear pattern in the northeast direction of the Akkuyu Nuclear Power Plant. The low-risk and potential risk zones cross the provincial boundary of Mersin province.

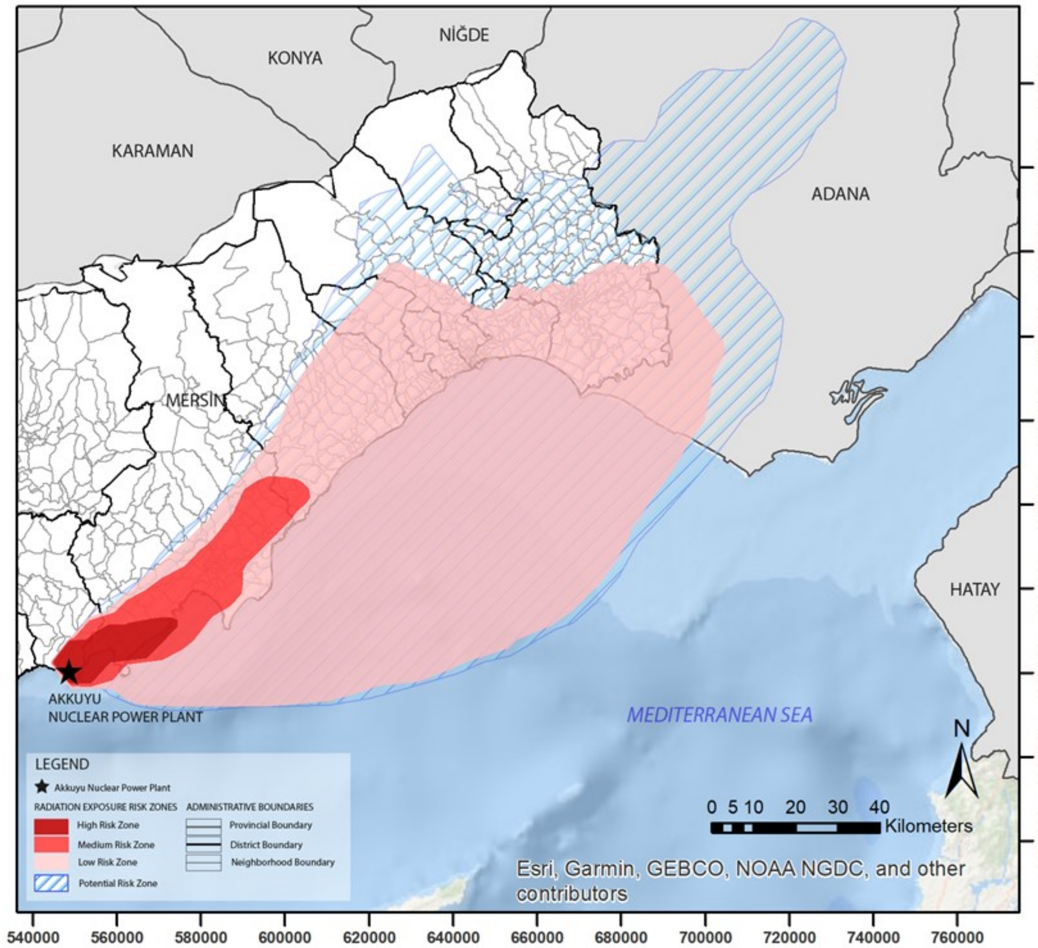

Figure 5.22. Radiation exposure risk classification map for Akkuyu Nuclear Power Plant: Scenario 2 day 2 (From 12.00 pm 16 May 2021 to 17 May 2021) (Grid size: 20x20 km)

Further risk classification analysis is made at the neighborhood level, and the map is shown in Figure 5.23. From the map, the area size of the affected neighborhoods is examined within the boundary of Mersin Province and shown in Table 5.5.

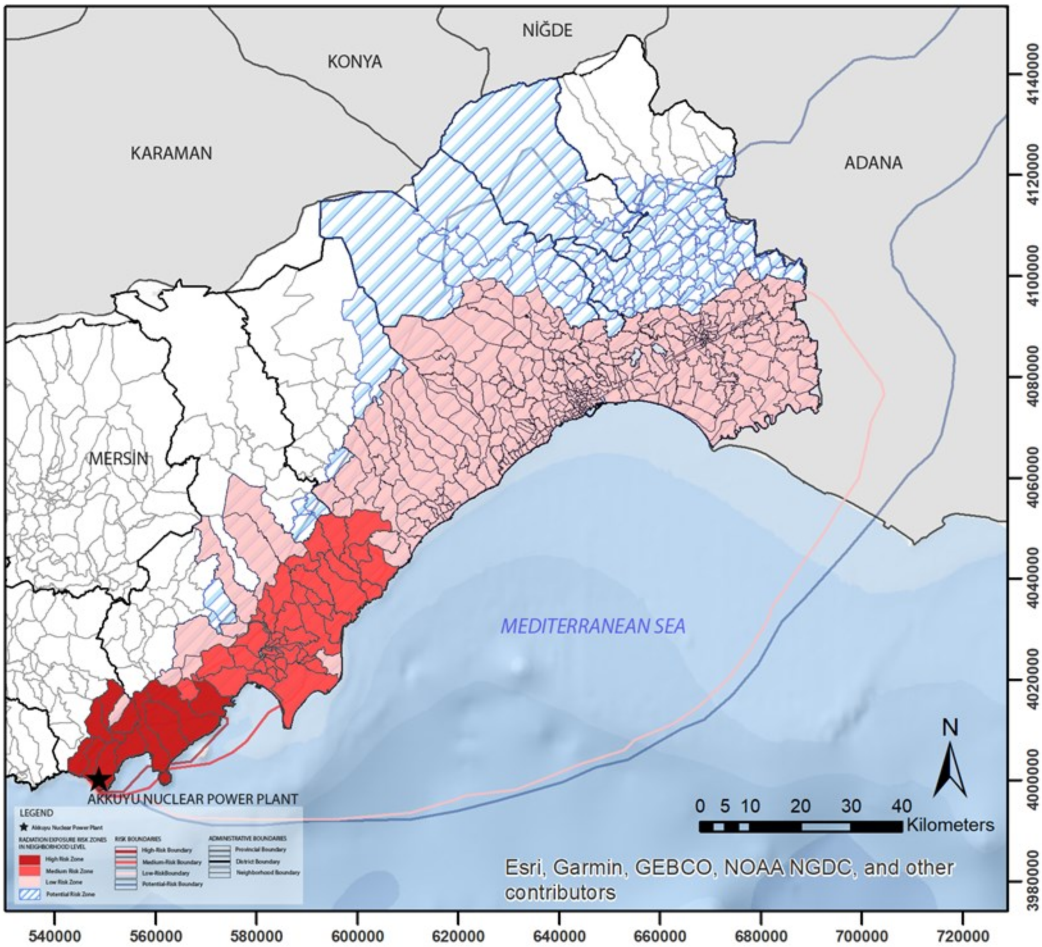

Figure 5.23. Radiation exposure risk classification map at the neighborhood level: Scenario 2 day 2 (From 12.00 pm 16 May 2021 to 17 May 2021) (Grid size: 20x20 km)

Table 5.5 *Area of radiation exposure risk classes: Scenario 1 day 3 (From 12.00 pm 15 May 2021 to 16 May 2021*

Radiation Exposure Risk Zones	Area (sq. km)	Percentage (%)
Potential Risk Zone	2649,0	38,8
Low Risk Zone	3047,3	44,6
Medium Risk Zone	756,3	11,1
High Risk Zone	375,6	5,5
TOTAL	6828,2	100,0

Table 5.5 identifies that the neighborhoods under the high-risk zone cover the smallest part of the affected area with 375.5 sq. km (or 5.5% of the total area size). The neighborhoods in the medium-risk zone have a 756.3 sq. km size, corresponding to 11.1% of the total area. The largest part of the total affected area for scenario 2, day 2, is 3047.3 sq. km (or 44.6% of total), under low radiation exposure risk. Lastly, the potential risk zone covers 2649 sq. km at the neighborhood level and corresponds to 38.8% of the total affected area.

The population distribution map on classified radiation exposure risk zones for scenario 2, day 2, is prepared to observe the affected population and is shown in Figure 5.24. From the map indicating the population distribution, the total population within the risk zones is identified and compared in the quantitative chart shown in Figure 5.25.

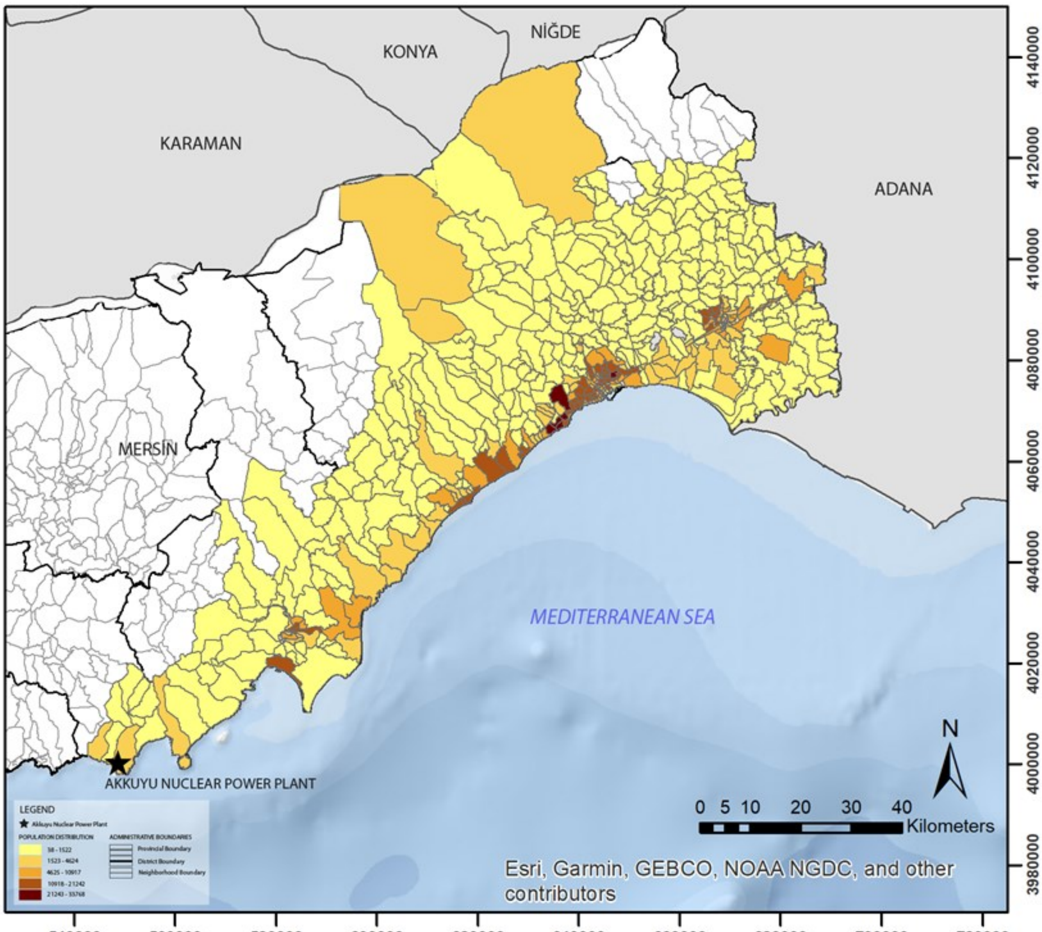

Figure 5.24. Population distribution map on radiation exposure risk zones: Scenario 2 day 2 (From 12.00 pm 16 May 2021 to 17 May 2021) (Grid size: 20x20 km)

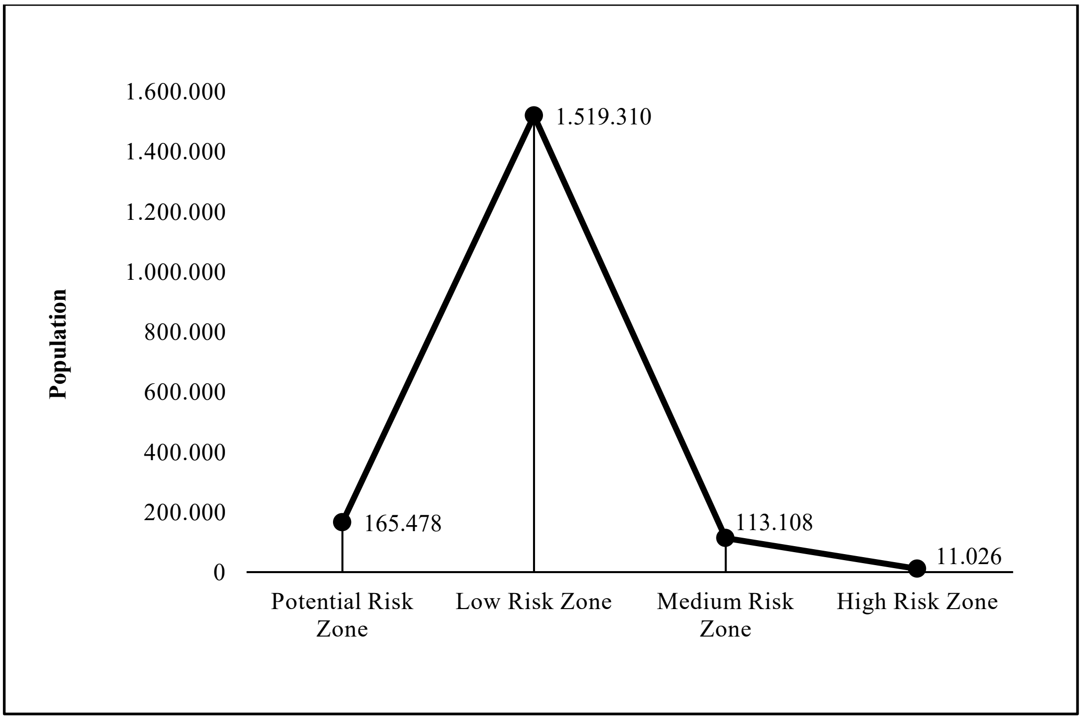

Figure 5.25. Quantitative chart displaying total population distribution on radiation exposure risk zones: Scenario 2 day 2 (From 12.00 pm 16 May 2021 to 17 May 2021)

In the quantitative chart of total population distribution on radiation exposure risk zones for scenario 2, day 2, it is denoted that the neighborhoods under high risk have the smallest population with 11,026 persons (or 0.6% of the total population). The population of neighborhoods under medium risk is 113,108 persons (or 6.3% of the total population). The largest affected population on the second day of scenario 2 is 1,519,310 (or 84% of the total population) and belongs to the neighborhoods under low radiation exposure risk. Lastly, the neighborhoods with potential risk have a considerable population of 165,478 persons (or 9.1% of the total population). Overall, the total evacuation demand is 1,808,922 persons.

On the last day of observations, the radioactive plume continues to move over to the East-Northeast direction by splitting from the source since the emission duration ends (See Figure 5.26). At the end of the first 4 hours, it starts shrinking and floats mostly over the Mediterranean Sea rather than inland. Then, it changes its path slightly to the North and covers the Southern part of the Tarsus district of Mersin.

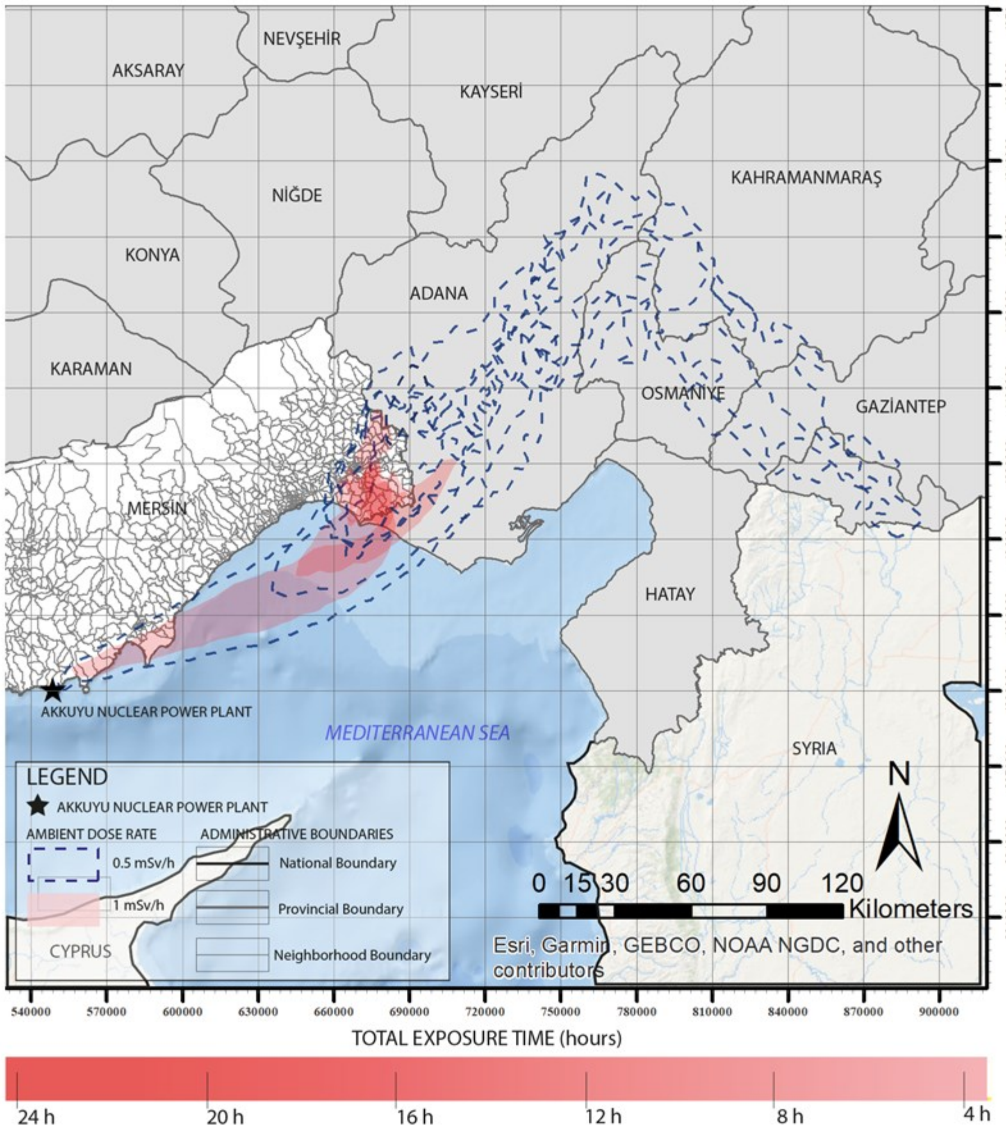

Figure 5.26. Superposed nuclear hazard map displaying total exposure time for Akkuyu Nuclear Power Plant: Scenario 2 day 3 (From 12.00 pm 17 May 2021 to 18 May 2021) (Grid size: 30x30 km)

The risk classification map by total exposure time for the last day of scenario 2 is shown in Figure 5.27. On the last day of scenario 2, only medium, low, and potential risk zones exist. The risk zones touch two different parts of Mersin province, the southern part of Silifke and Tarsus districts. The potential risk zone crosses the provincial boundary of Mersin province and covers some parts of Adana, Osmaniye, and Gaziantep provinces.

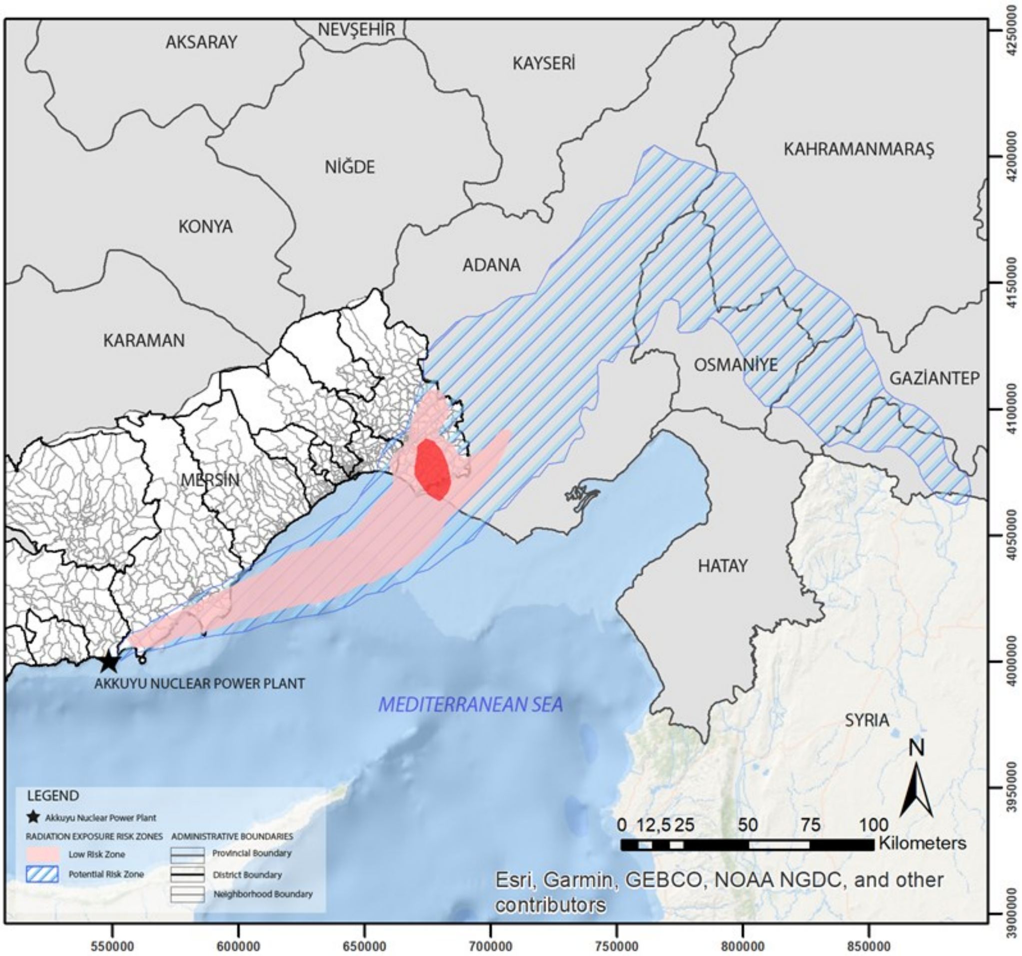

Figure 5.27. Radiation exposure risk classification map for Akkuyu Nuclear Power Plant: Scenario 2 day 3 (From 12.00 pm 17 May 2021 to 18 May 2021) (Grid size: 50x50 km)

Further risk classification analysis is made at the neighborhood level, and the map is shown in Figure 5.28. From the map, the area size of the affected neighborhoods is examined within the boundary of Mersin Province and shown in Table 5.6.

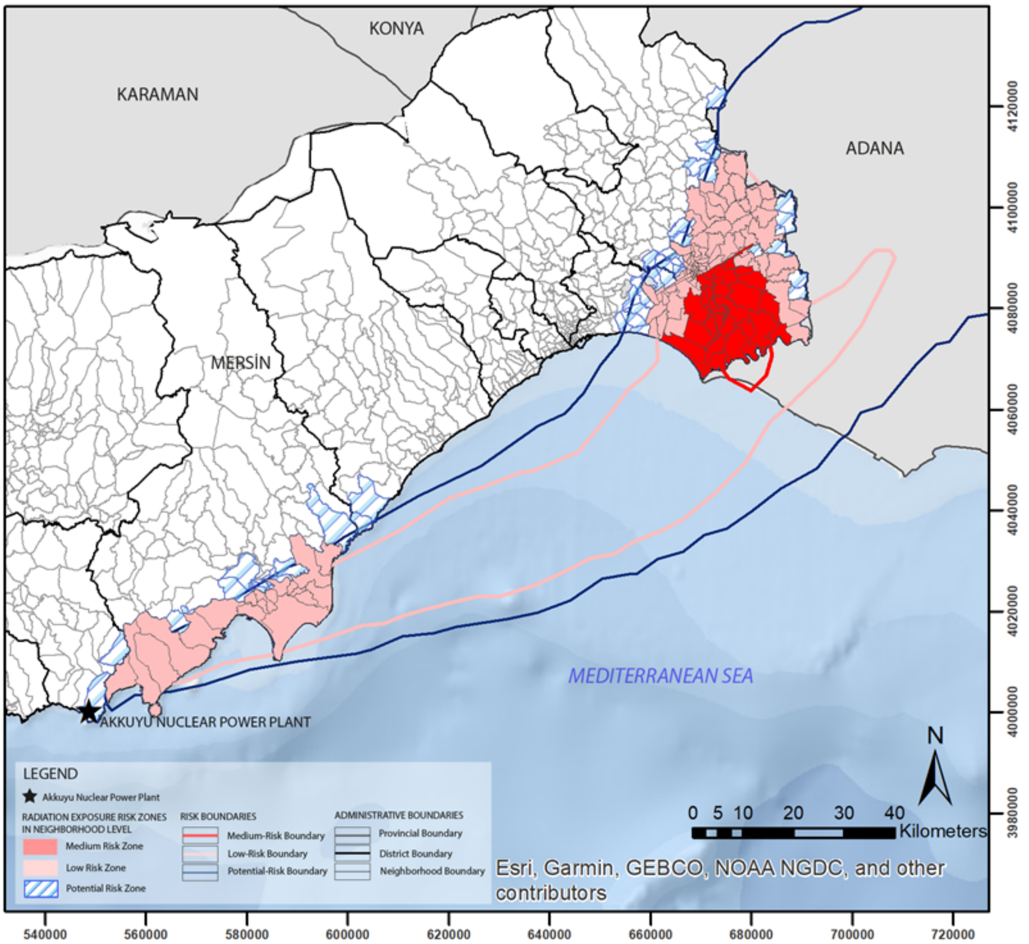

Figure 5.28. Radiation exposure risk classification map at the neighborhood level: Scenario 2 day 3 (From 12.00 pm 17 May 2021 to 18 May 2021) (Grid size: 20x20 km)

Table 5.6 *Area of radiation exposure risk classes: Scenario 1 day 3 (From 12.00 pm 17 May 2021 to 18 May 2021*

Radiation Exposure Risk Zones	Area (sq. km)	Percentage (%)
Potential Risk Zone	476,1	26,8
Low Risk Zone	968,0	54,5
Medium Risk Zone	331,6	18,7
TOTAL	1775,7	100,0

Table 5.6 shows that the neighborhood under medium risk covers the smallest part of the total affected area, with 331,6 sq. km size corresponding to 18.7% of the total affected area. In contrast, the neighborhood under the low risk has the largest area size with 968 sq. km (or 54.5% of the total). Also, the neighborhoods under potential risk cover 476.1 sq. km, corresponding to 26.8% of the total affected area.

The population distribution map on classified radiation exposure risk zones for scenario 2, day 3, is prepared to observe the affected population and is shown in Figure 5.29. From the map indicating the population distribution, the total population within the risk zones is identified and compared in the quantitative chart shown in Figure 5.30.

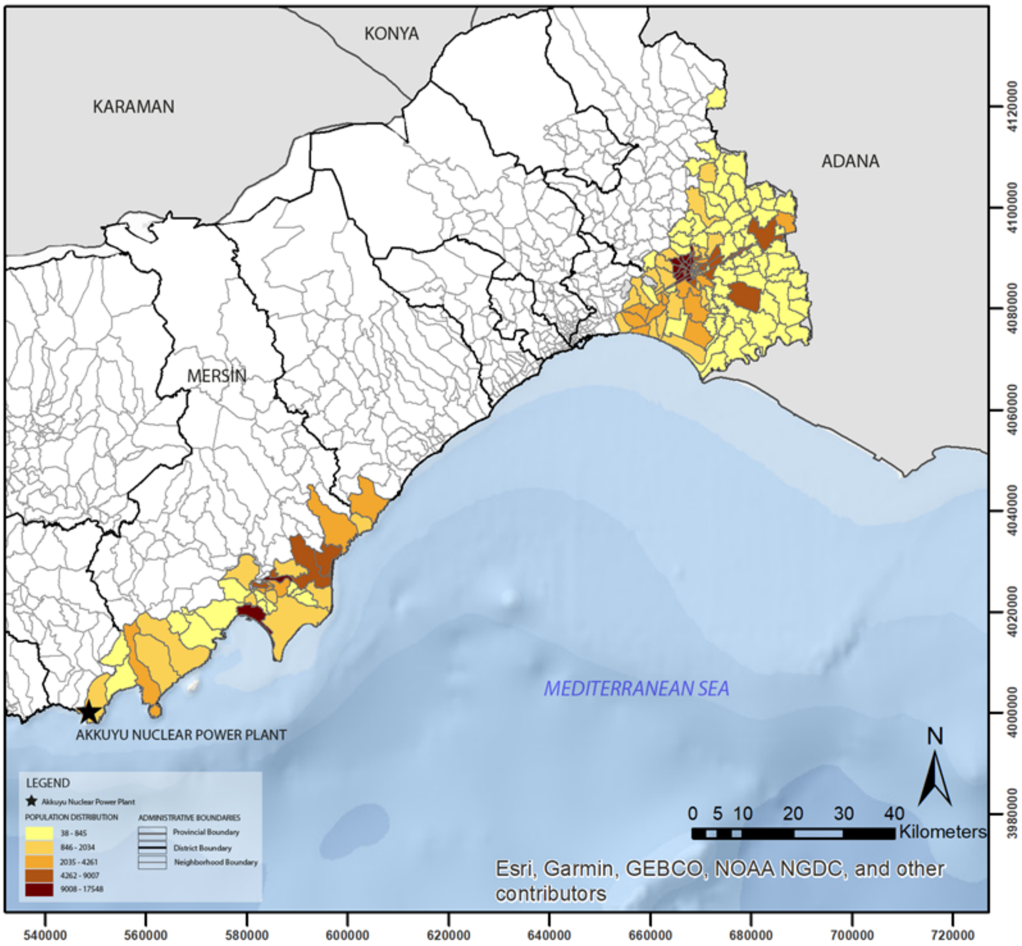

Figure 5.29. Population distribution map on radiation exposure risk zones: Scenario 2 day 3 (From 12.00 pm 17 May 2021 to 18 May 2021) (Grid size: 20x20 km)

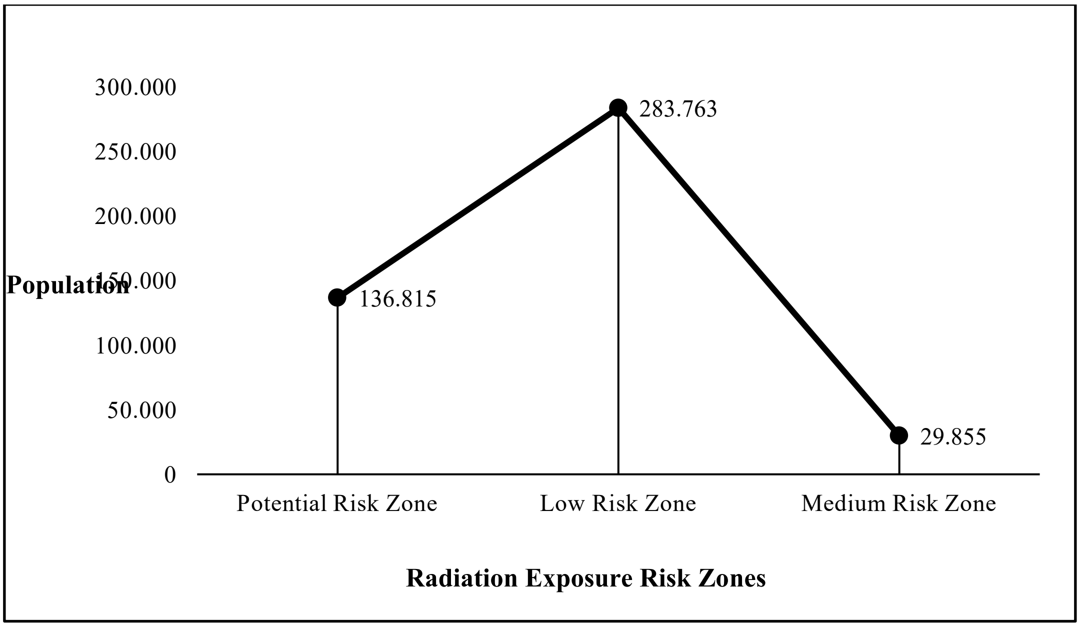

Figure 5.30. Quantitative chart displaying total population distribution on radiation exposure risk zones: Scenario 2 day 2 (From 12.00 pm 17 May 2021 to 18 May 2021)

In the quantitative chart of total population distribution on radiation exposure risk zones for scenario 2, day 3, it is identified that the neighborhoods with medium risk have the smallest population with 29,855 persons (or 6.6% of the total population). The largest population of the total affected population is 283,763 persons (or 63% of the total population) and situates in the neighborhood under the low-risk zone. Additionally, the neighborhoods with potential risk have 136,815 persons corresponding to 30.4% of the total affected population. Overall, the total evacuation demand is 450,433 persons.

5.3 Results on Daily Overlay: Scenario 3

In scenario 3, this research simulates the dispersion of cumulative release of Cs-137 and I-131 from a hypothetical accident in the Akkuyu Nuclear Power Plant between 01 December and 04 December 2021. On the first day of observations, the radioactive plume starts spreading through the East-Southeast direction and slightly changes its direction from the East-Southeast to the South until the end of the day

(See Figure 5.31.). Overall, the plume mostly covers the Mediterranean Sea, a relatively large part of the Turkish Republic of Northern Cyprus, and a small part of the Greek Cypriot Administration of Southern Cyprus. Moreover, the first day's observations in this scenario indicate that the plume starts moving to inland Turkey every time step.

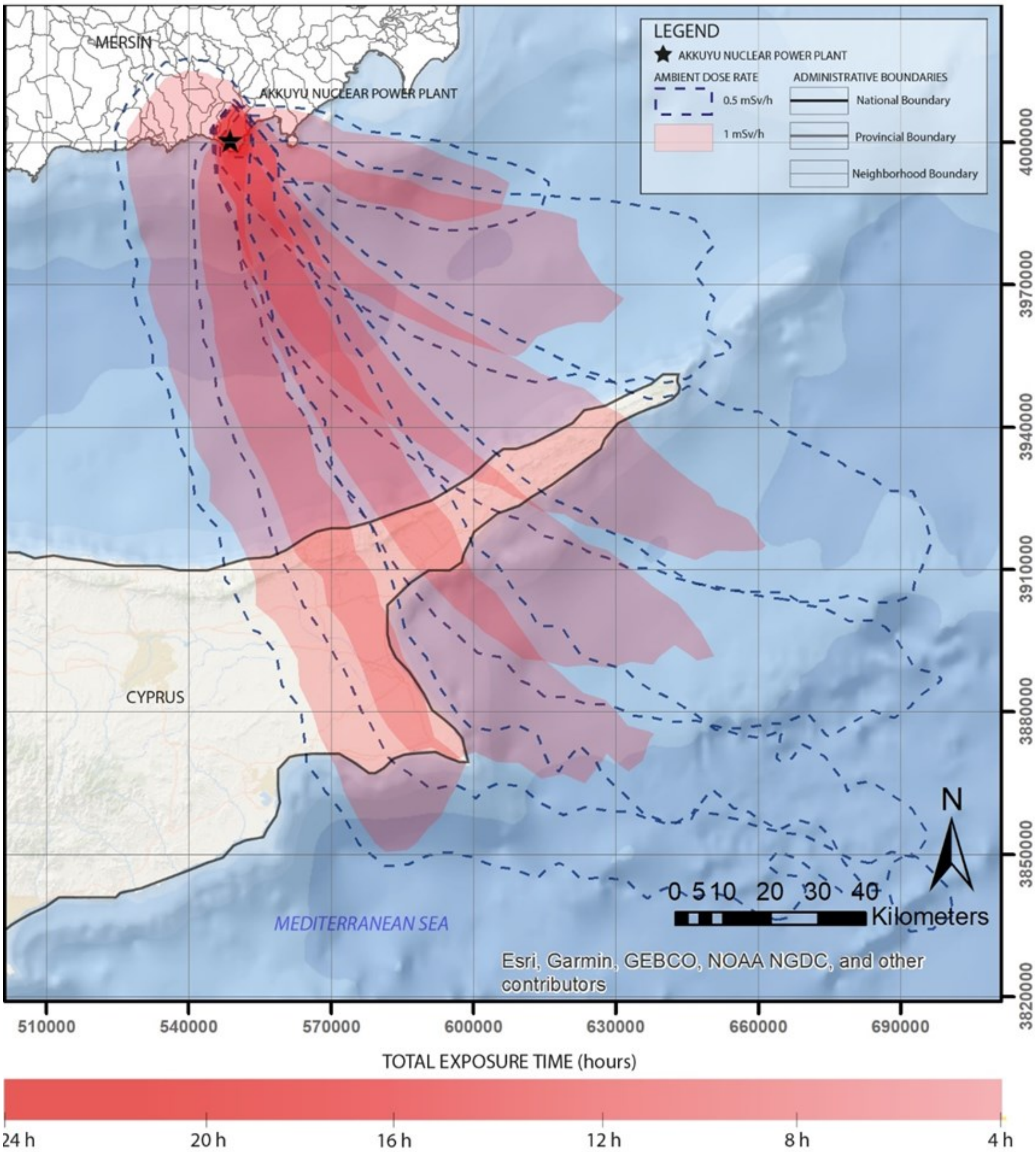

Figure 5.31. Superposed nuclear hazard map displaying total exposure time for Akkuyu Nuclear Power Plant: Scenario 3 day 1 (From 12.00 pm 01 December 2021 to 02 December 2021) (Grid size: 30x30 km)

The risk classification map by total exposure time for the first day of scenario 3 is shown in Figure 5.32. On the first day of scenario 3, the risk zones cover a relatively small area of the northern part of Akkuyu Nuclear Power Plant, and the low and potential risk zones reach the northeastern part of Cyprus.

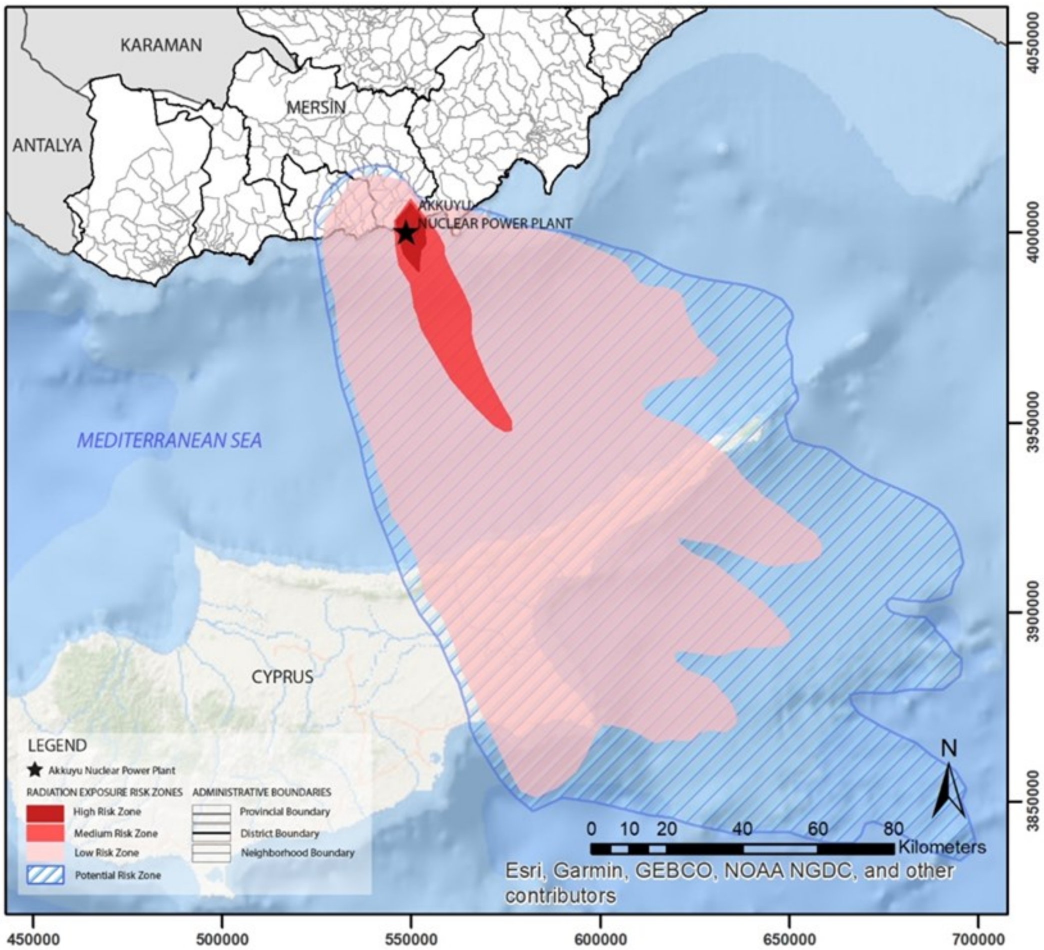

Figure 5.32. Radiation exposure risk classification map for Akkuyu Nuclear Power Plant: Scenario 3 day 1 (From 12.00 pm 01 December 2021 to 02 December 2021) (Grid size: 50x50 km)

The risk classification analysis is made at the neighborhood level, and the map is shown in Figure 5.33. From the map, the area size of the affected neighborhoods is examined within the boundary of Mersin Province and shown in Table 5.7.

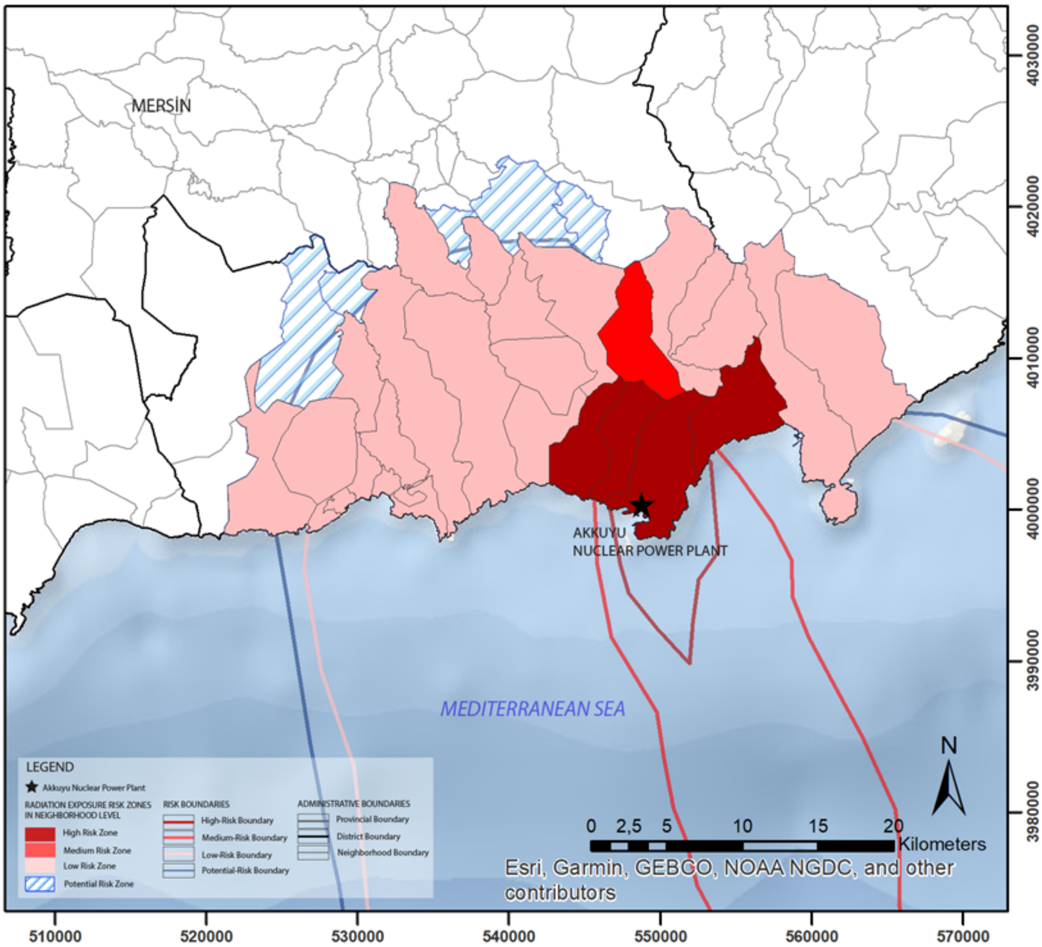

Figure 5.33. Radiation exposure risk classification map at the neighborhood level: Scenario 3 day 1 (From 12.00 pm 01 December 2021 to 02 December 2021) (Grid size: 20x20 km)

Table 5.7 *Area of radiation exposure risk classes: Scenario 3 day 2 (From 12.00 pm 02 December 2021 to 03 December 2021)*

Radiation Exposure Risk Zones	Area (sq. km)	Percentage (%)
Potential Risk Zone	92,7	12,9
Low Risk Zone	502,2	70,1
Medium Risk Zone	24,5	3,4
High Risk Zone	97,1	13,5
TOTAL	716,5	100

Table 5.7 indicates that the high-risk and potential risk zones cover approximately the same area size, 97.1 sq. km (or 13.5% of the total area) and 12.9 sq. km (12.9% of the total area), respectively. The medium-risk zone has the smallest part of the affected area and covers only 3.4% with a 24.5 sq. km area size, while the low-risk zone covers 502.2 sq. km corresponding to the 70.1% of the total, the largest part of the affected area.

The population distribution map on classified radiation exposure risk zones for scenario 3, day 1, is prepared to observe the affected population and is shown in Figure 5.34. From the map indicating the population distribution, the total population within the risk zones is identified and compared in the quantitative chart shown in Figure 5.35.

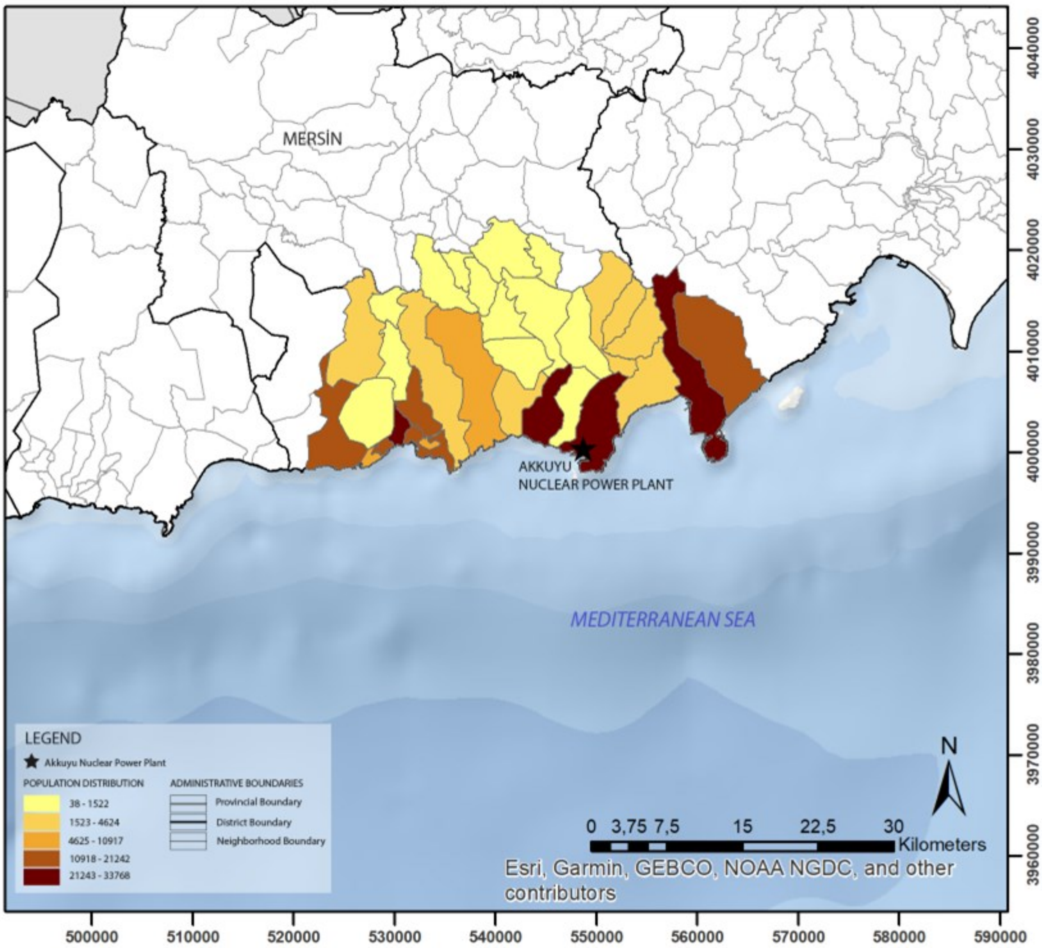

Figure 5.34. Population distribution map on radiation exposure risk zones: Scenario 3 day 1 (From 12.00 pm 01 December 2021 to 02 December 2021) (Grid size: 10x10 km)

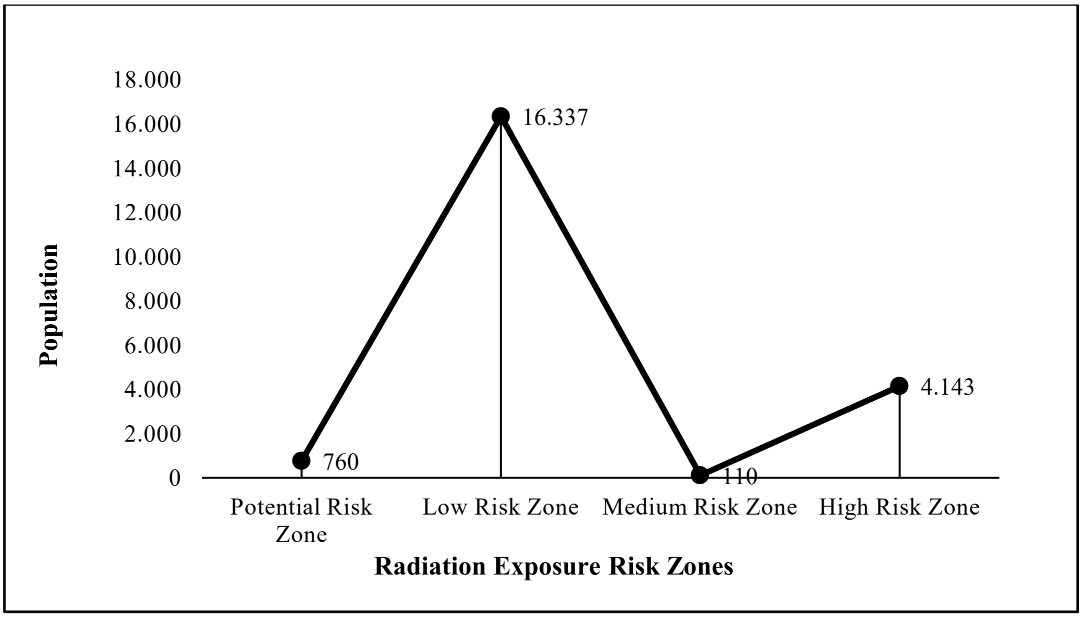

Figure 5.35. Quantitative chart displaying total population distribution on radiation exposure risk zones: Scenario 3 day 1 (From 12.00 pm 01 December 2021 to 02 December 2021)

According to the quantitative chart of total population distribution on radiation exposure risk zones for scenario 3, day 1, it is identified that the population of the neighborhoods under high risk is 4,143, corresponding to 19.4% of the total population. The smallest affected population, 110 persons (or 0.5% of the total population), situates in a neighborhood with medium risk. The neighborhoods under the low-risk zone have the largest affected population, with 16,337 persons (or 76.5% of the total population) on the first day of scenario 3. Lastly, the population of neighborhoods under potential risk is 760 persons corresponding to 3.6% of the total affected population. Overall, the total evacuation demand is 21,350 persons.

On the second day, the radioactive plume splits into two pieces, and a relatively large part of it moves inland of Turkey in the North direction (See Figure 5.36.). Thereafter, the plume changes its path slightly from the North to the East-Northeast direction by expanding. At the end of 20 hours, it turns its route to the West-Northwest direction by splitting into four pieces.

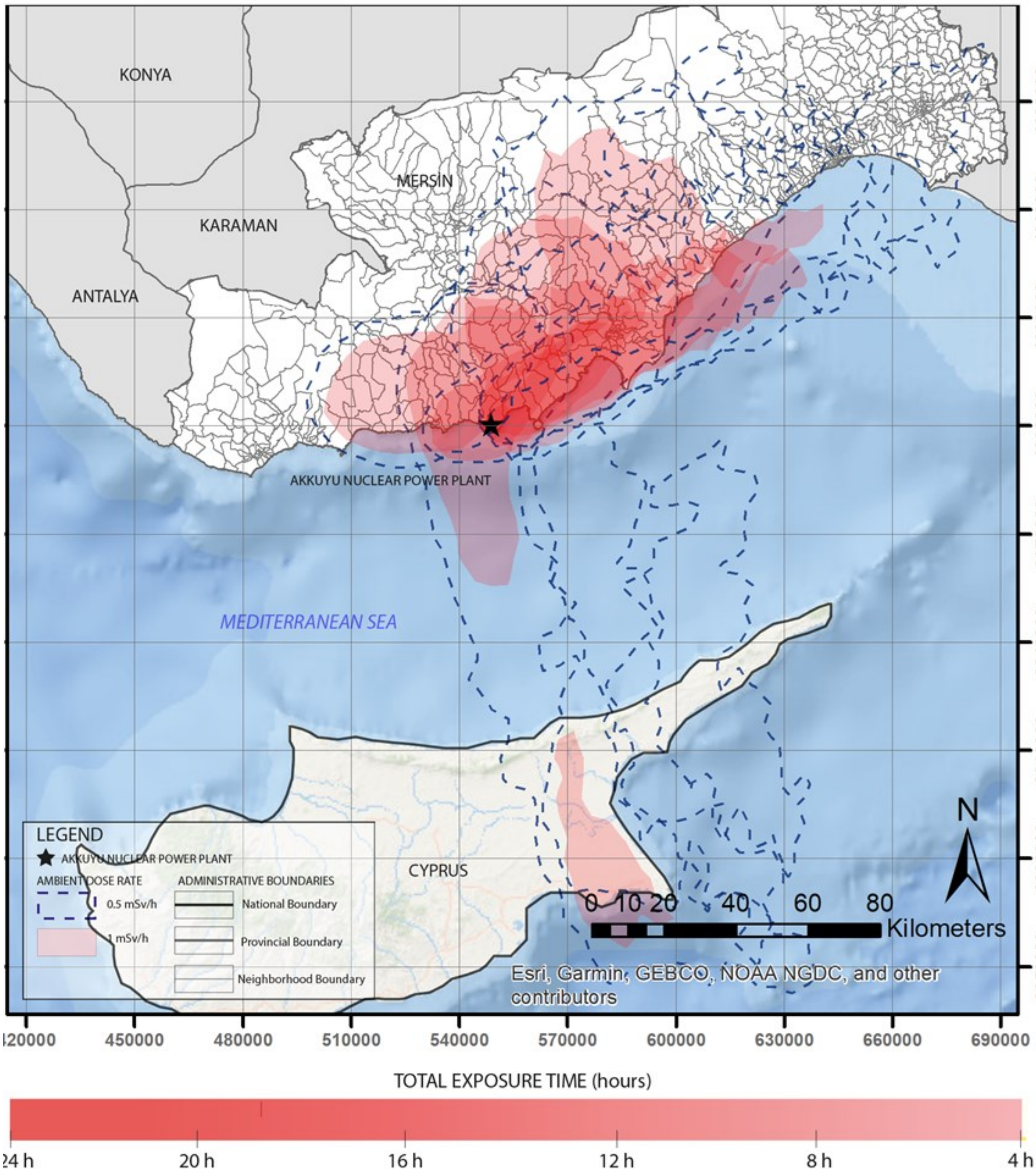

Figure 5.36. Superposed nuclear hazard map displaying total exposure time for Akkuyu Nuclear Power Plant: Scenario 3 day 2 (From 12.00 pm 02 December 2021 to 03 December 2021) (Grid size: 30x30 km)

The risk classification map of the second day of scenario 3 (See Figure 5.37). indicates that the risk zones cover most of Mersin's surface area, and the potential risk zone also covers the northeastern part of Cyprus.

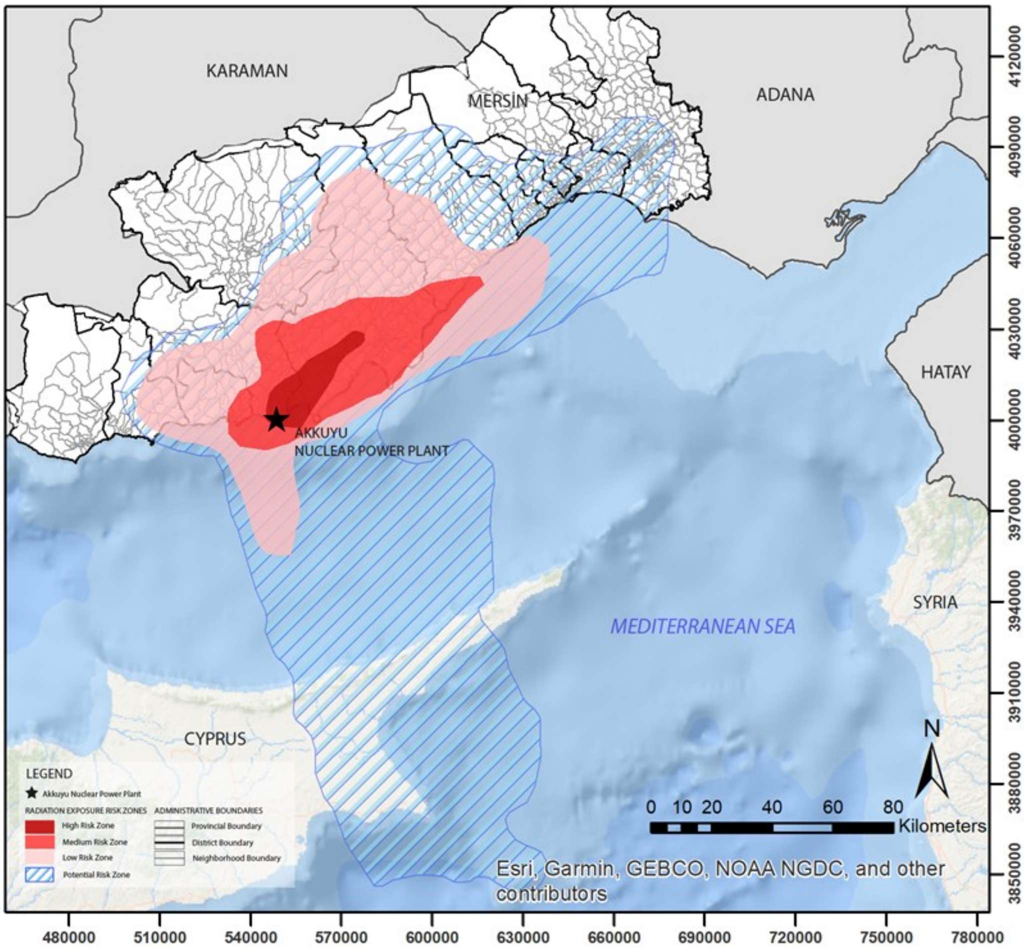

Figure 5.37. Radiation exposure risk classification map for Akkuyu Nuclear Power Plant: Scenario 3 day 2 (From 12.00 pm 02 December 2021 to 03 December 2021) (Grid size: 30x30 km)

The risk classification analysis is made at the neighborhood level, and the map is shown in Figure 5.38. From the map, the area size of the affected neighborhoods is examined within the boundary of Mersin Province and shown in Table 5.8.

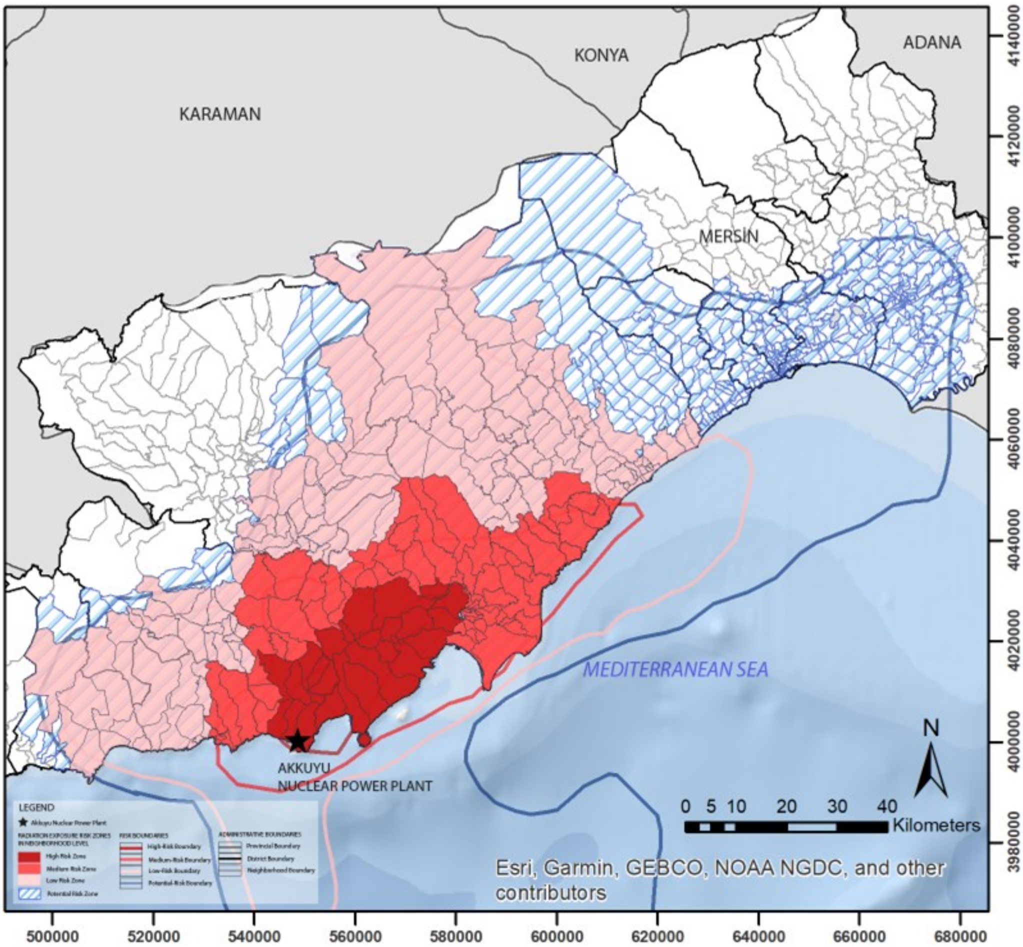

Figure 5.38. Radiation exposure risk classification map at the neighborhood level: Scenario 3 day 2 (From 12.00 pm 02 December 2021 to 03 December 2021) (Grid size: 20x20 km)

Table 5.8 *Area of radiation exposure risk classes: Scenario 3 day 2 (From 12.00 pm 02 December 2021 to 03 December 2021)*

Radiation Exposure Risk Zones	Area (sq. km)	Percentage (%)
Potential Risk Zone	3440,7	36,0
Low Risk Zone	3846,2	40,2
Medium Risk Zone	1532,7	16,0
High Risk Zone	740,9	7,7
TOTAL	9560,5	100

Table 5.8 identifies that the neighborhoods under high-risk cover 7.7% of the total affected area with 740.9 sq. km, and medium risk covers 1532.7 sq. km corresponding to 16% of the total. The neighborhoods under low-risk zone cover 3846.2 sq. km (or 40.2% of the total), the largest area size of the total affected area. The area size of the neighborhoods under potential risk is 3440.7 sq. km (or 36% of the total), and it is relatively close to the area size of the neighborhoods under high risk.

The population distribution map on classified radiation exposure risk zones for scenario 3, day 2, is prepared to observe the affected population and is shown in Figure 5.39. From the map indicating the population distribution, the total population within the risk zones is identified and compared in the quantitative chart shown in Figure 5.40.

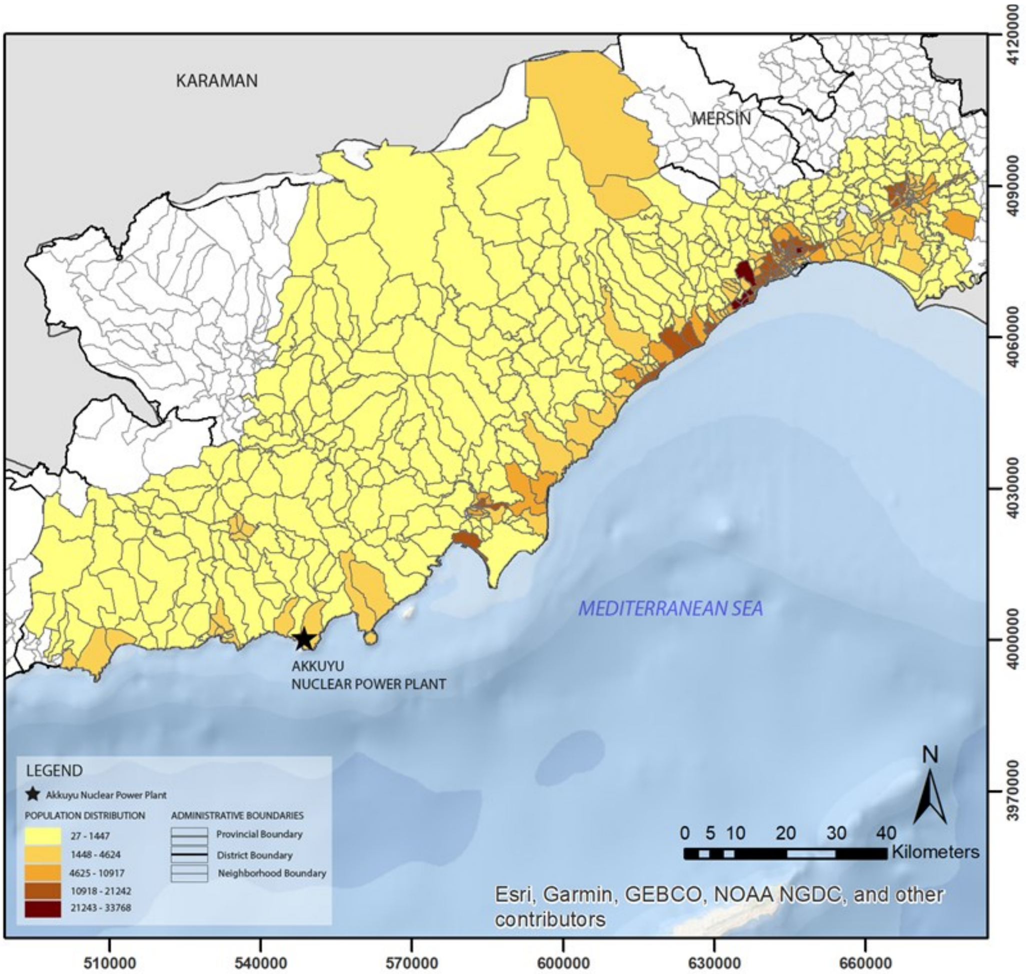

Figure 5.39. Population distribution map on radiation exposure risk zones: Scenario 3 day 2 (From 12.00 pm 02 December 2021 to 03 December 2021) (Grid size: 30x30 km)

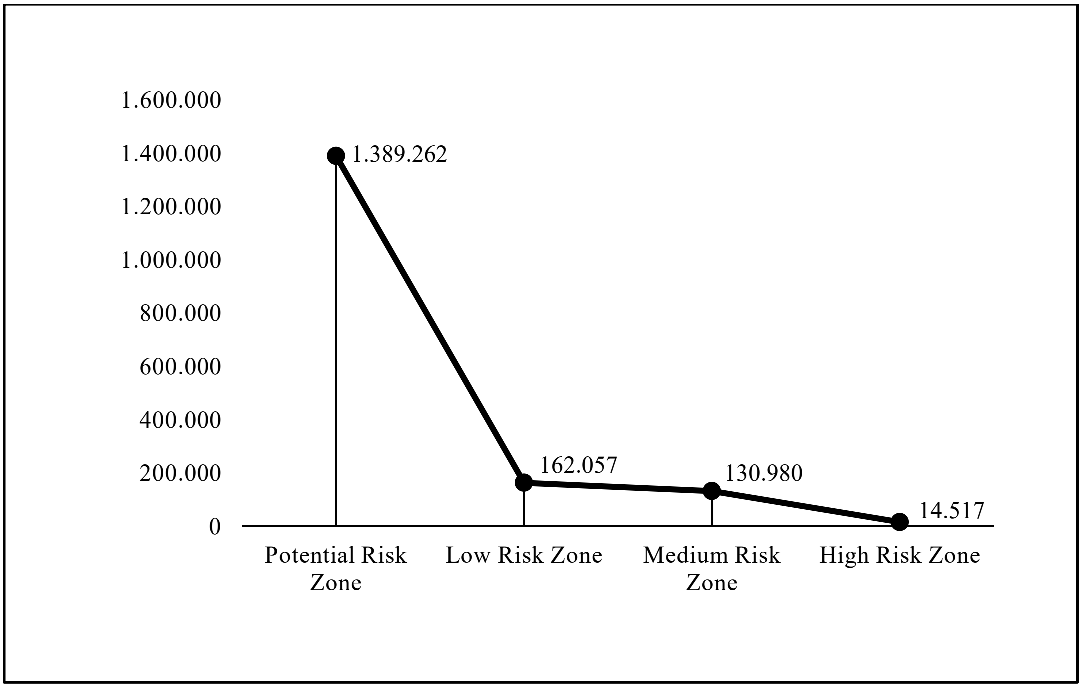

Figure 5.40. Quantitative chart displaying total population distribution on radiation exposure risk zones: Scenario 3 day 2 (From 12.00 pm 02 December 2021 to 03 December 2021)

According to the quantitative chart of total population distribution on radiation exposure risk zones of scenario 3, day 2, the neighborhoods' population situated on high risk is 14,517 persons corresponding to 0.9% of the total population. 130,980 persons live in the neighborhoods under medium risk, which is 7.7% of the total population, and 162,057 persons (or 9.6% of the total) live in low-risk neighborhoods. The largest portion of the affected population is 1,389,262 persons (or 81.9% of the total) who lives in neighborhoods with potential radiation risk. Overall, the total evacuation demand is 1,696,816 persons.

On the last day, the radioactive plume continues moving in a West-Northwest direction; however, it starts shrinking and splitting into pieces, and the center of it starts moving away from the source (See Figure 5.41).

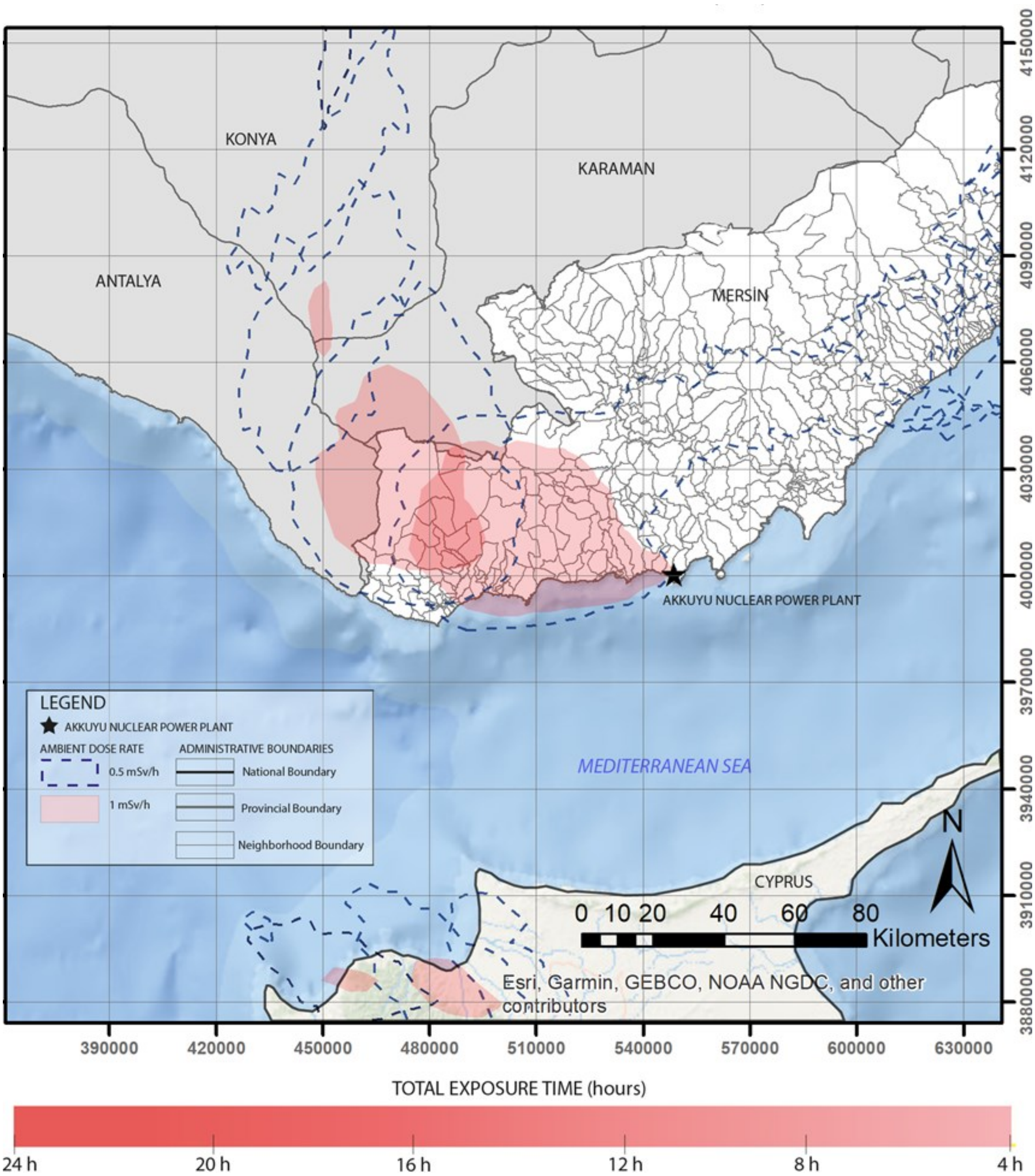

Figure 5.41. Superposed nuclear hazard map displaying total exposure time for Akkuyu Nuclear Power Plant: Scenario 3 day 3 (From 12.00 pm 03 December 2021 to 04 December 2021) (Grid size: 30x30 km)

The risk classification map by total exposure time for the last day of scenario 3 is shown in Figure 5.42. The risk classification map denotes that only low and potential risk zones exist on the last day of scenario 3. The low-risk zone covers the northwestern part of Mersin province. In contrast, the potential risk zone covers an area along Mersin, and it reaches Antalya, Karaman, and Konya, crossing the provincial boundary of Mersin.

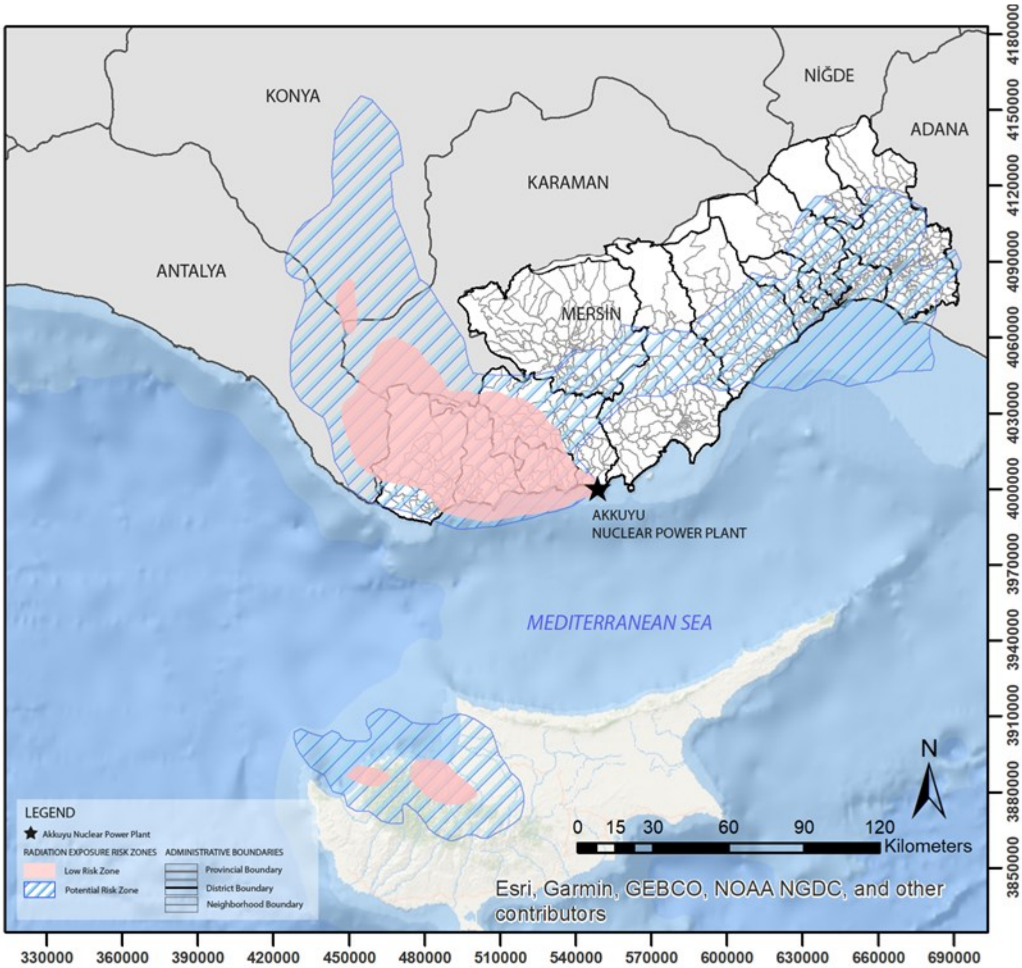

Figure 5.42. Radiation exposure risk classification map for Akkuyu Nuclear Power Plant: Scenario 3 day 3 (From 12.00 pm 03 December 2021 to 04 December 2021 (Grid size: 30x30 km)

Further risk classification analysis is made at the neighborhood level, and the map is shown in Figure 5.43. From the map, the area size of the affected neighborhoods is examined within the boundary of Mersin Province and shown in Table 5.9.

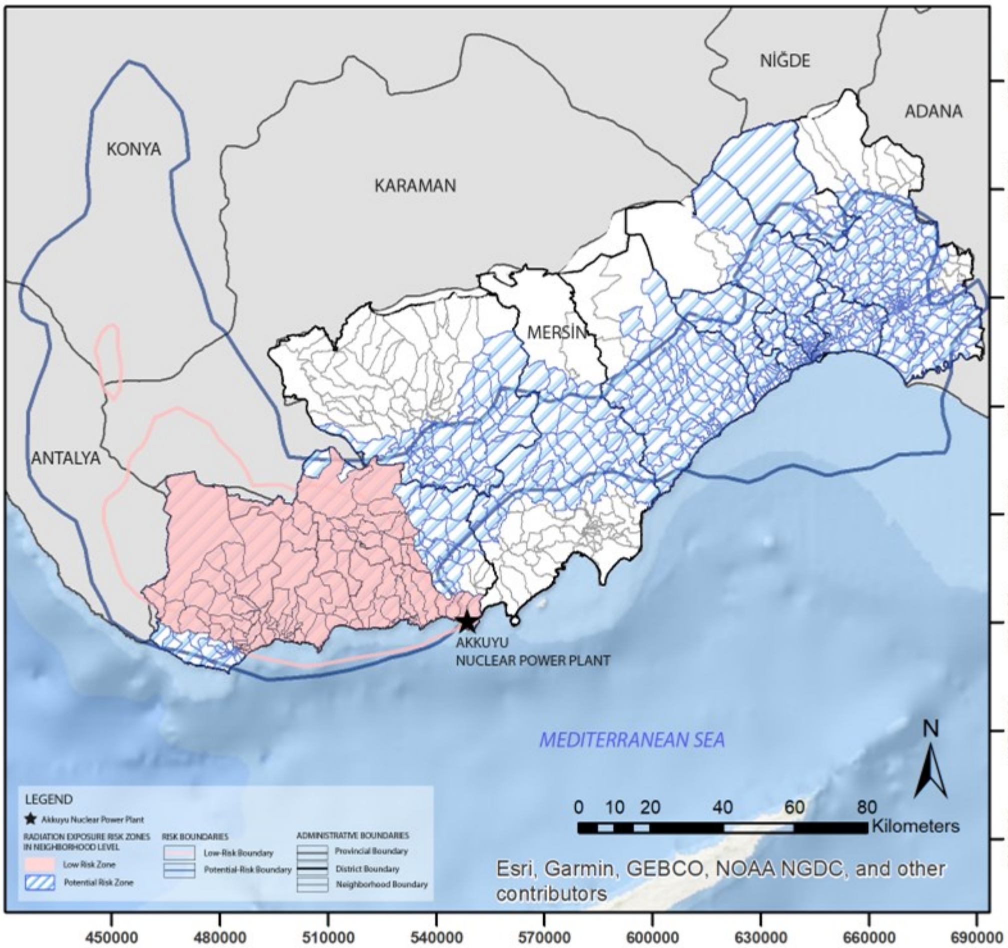

Figure 5.43. Radiation exposure risk classification map at the neighborhood level: Scenario 3 day 3 (From 12.00 pm 03 December 2021 to 04 December 2021) (Grid size: 30x30 km)

Table 5.9 *Area of radiation exposure risk classes: Scenario 3 day 3 (From 12.00 pm 03 December 2021 to 04 December 2021)*

Radiation Exposure Risk Zones	Area (sq. km)	Percentage (%)
Potential Risk Zone	7756,0	71,2
Low Risk Zone	3135,9	28,8
TOTAL	10891,9	100

According to Table 6.9, it is identified that the neighborhoods under low-risk cover 28.8% of the total affected area with a 3135.8 sq. km area size. In comparison, the neighborhoods at potential risk cover most of the affected area with 7756 sq. km (or 71.2% of the total).

The population distribution map on classified radiation exposure risk zones for scenario 3, day 3, is prepared to observe the affected population and is shown in Figure 5.44. From the map indicating the population distribution, the total population within the risk zones is identified and compared in the quantitative chart shown in Figure 5.45.

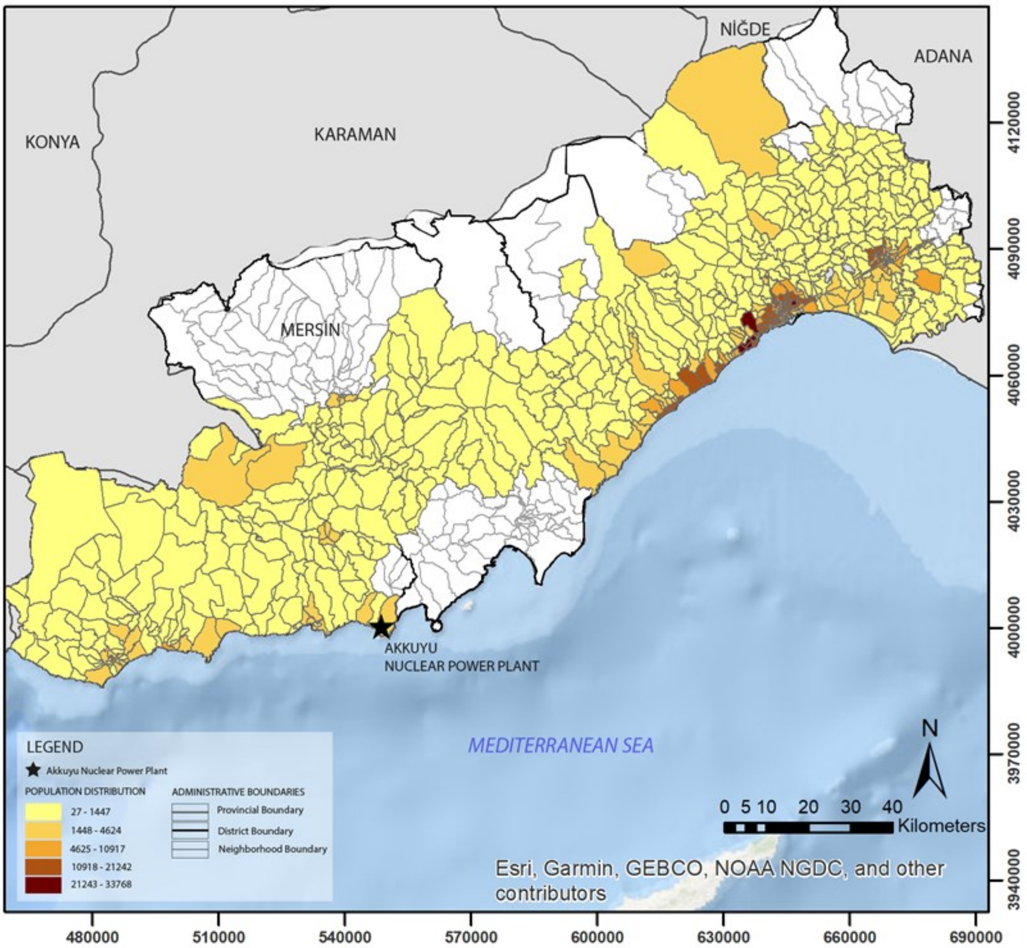

Figure 5.44. Population distribution map on radiation exposure risk zones: Scenario 3 day 3 (From 12.00 pm 03 December 2021 to 04 December 2021) (Grid size: 30x30 km)

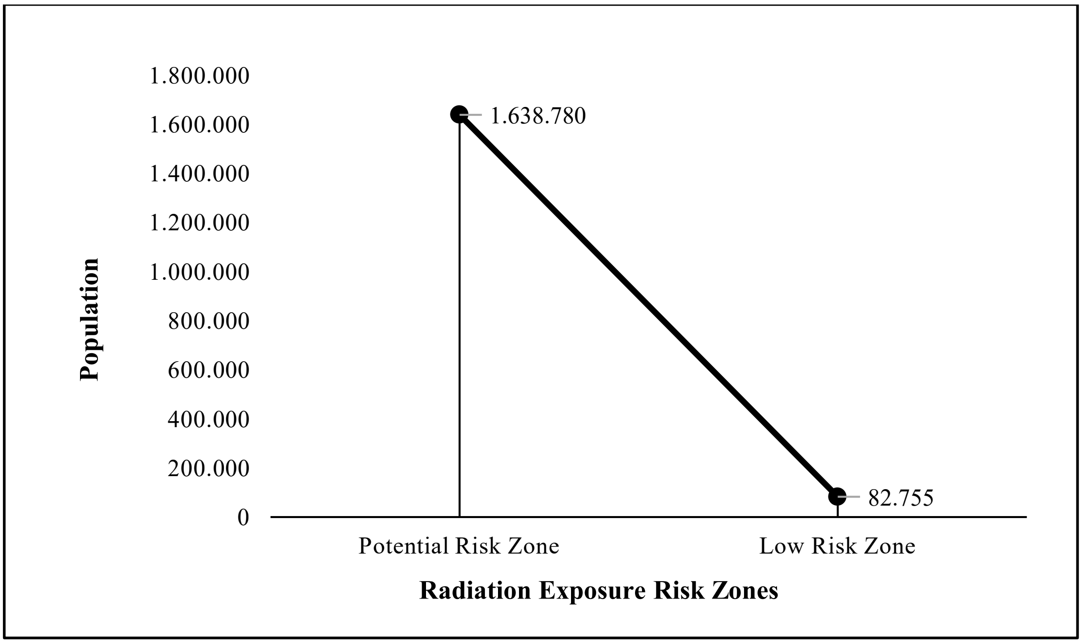

Figure 5.45. Quantitative chart displaying total population distribution on radiation exposure risk zones: Scenario 3 day 3 (From 12.00 pm 03 December 2021 to 04 December 2021)

In the quantitative chart of total population distribution on radiation exposure risk zones: scenario 3, day 3, it is identified that 82,755 persons live in the neighborhoods under low risk. In comparison, 1,638,780 persons situate in the neighborhoods under potential risk. Overall, the total evacuation demand is 1,721,535 persons.

5.4 Discussions

This research considered the unforeseen severe nuclear power plant accidents as a problem even if the probability of such accidents is regarded as low and created a hypothetical accident scenario to observe the consequences. It focused on Akkuyu-NPP as a case study within the scope of the problem statement of this research, and it revealed how the atmospheric dispersion pattern of ionizing radiation affected the identification of evacuation zones.

The scenarios within the scope of this research were highly dependent on the wind parameters, which are the main parameter affecting the dispersion pattern of the radioactive plume. Scenario 1 results showed that the main path of the radioactive plume followed the west and west-southwest direction from the Akkuyu Nuclear Power Plant. In contrast, Scenario 2 results showed that the radioactive plume dispersed mainly in the northeast direction of the Akkuyu Nuclear Power Plant. Scenario 3 results indicated the radioactive plume followed a different pattern than scenarios 1 and 2. The radioactive plume in this scenario dispersed in more than one direction and followed an irregular pattern. This research identified the evacuation zones and demands considering the pathway of the radioactive plume, indicating that the plume pathway directly affects them. For example, scenarios 1 and 2 present relatively opposite characteristics; it is observed that the higher evacuation demand in scenario 2 compared to scenario 1 since the plume direction in scenario 2 reach the Mersin city center, the densely populated area. Consequently, the scenario base results of this research revealed the importance of meteorological conditions in identifying the evacuation zones and in estimating the evacuation demand. Besides, the research indicated that the further steps of evacuation planning require a comprehensive meteorological condition analysis with the meteorological data, including the sigma coordinate system, to observe the effects of topographical features on atmospheric dispersion.

The research identified the evacuation zones with an ambient dose rate larger than or equal to 1 mSv/h and the potential evacuation zones with an ambient dose rate smaller than 1 mSv/h and larger than or equal to 0.5 mSv/h. The aim of identifying the potential evacuation zones is to indicate that evacuation preparation may also be implemented in these zones since the radioactive plume may expand. The results indicated that the possible evacuation zones included a considerably high number of persons, and the population situated in these zones should be regarded in further steps of evacuation planning. Besides, the results revealed the affected areas and population if the radioactive plumes expand to the possible evacuation zone boundaries, so the evacuation destinations should be identified outside these boundaries.

5.5 Akkuyu-NPP Evacuation Planning Recommendations

The EAI report for Akkuyu-NPP states that the Akkuyu-NPP is equipped with high-tech products and permanent new technological solutions providing high-level quality in nuclear safety and radiation safety. Even if the safe design and high technology help reduce the risk of accidents, the risk of severe accidents has critical consequences on the living and non-living environment and future generations. Hence, it is essential to develop the appropriate emergency response involving evacuation plans, in which general objectives are to reduce the risk or to mitigate the consequences of the accident and reduce the adverse health effects (Lauritzen et al., 1998).

The scope of this research is to provide the initial steps of evacuation planning for Akkuyu-NPP. The nuclear hazard maps prepared using atmospheric dispersion models identify the hazard zones resulting in the hypothetical accident scenario for Akkuyu-NPP and further identify the evacuation zones. Subsequently, overlaying the geographical distribution of the total population to the evacuation zones estimates the evacuation demand within the provincial boundary of Mersin for three different meteorological conditions. Further recommendations for Akkuyu-NPP evacuation planning are in following:

- Evacuation demand should be re-estimated regarding the demand profile defined in the report, Criteria for Development of ETE Studies, to precisely estimate the operational cost of evacuation.
- The EAI report for Akkuyu-NPP states that topographic features indigenous to the region contribute to the increase in nuclear contamination concentration in nuclear emergencies. The site analysis involving the detailed land use of Akkuyu-NPP surroundings should be mapped to detect the

possible safe zones in a nuclear emergency. The safe zones should be identified outside the possible evacuation zone defined in this research regarding the possibility of varying meteorological conditions and changing the nuclear fallout profile, such as expanding its range or changing its direction. The safe zones should have sufficient capacity and basic living requirements corresponding to the evacuation demand. The exit points reaching the safe zones should satisfy the evacuation demand to prevent the bottlenecks causing potential traffic accidents, and to avoid protracting the evacuation time, causing increased radiation exposure.

- The EAI report for Akkuyu-NPP states that the existing transportation network prevailing around the Akkuyu-NPP has several undesirable features obstructing the emergency response actions, such as insufficient alternative transportation routes. The capacity of the roadway network should be analyzed to observe whether it is sufficient to correspond with the evacuation demand considering various scenario-based conditions and driver behavior. Suppose the evacuation demand is higher than the existing roadway capacity. In that case, the optimized solutions in evacuation routing, such as alternative transportation routes, should be generated to reduce the evacuation time and prevent delays during the evacuation operation.
- The efficiency of the evacuation operation should be tested by the evacuation time estimations under different conditions. In that case, it is possible to observe whether the calculated time estimations are adequate to clear the evacuation zone or not. Further improvements in evacuation planning for Akkuyu-NPP can be achieved by evaluating the evacuation time estimations.
- The efficiency of evacuation operation is directly related to urban planning; however, the requirements of evacuation planning steps have not yet corresponded/supported with urban planning policies. Therefore, the city (Mersin) should be designed/planned according to the prepared evacuation plans to correspond with the evacuation of numerous people. In that case, it is possible to mitigate the potential consequences of radiation exposure.

Evacuation planning is a comprehensive work hard to execute; however, it is an essential countermeasure in severe nuclear power plant accidents to minimize radiation exposure. This research is prepared to indicate the importance and necessity of an evacuation plan for Akkuyu-NPP. Turkey's responsible authorities have not yet prepared the off-site evacuation plan for Akkuyu-NPP. The probabilistic scenario-based results of this research reveal that a comprehensive evacuation plan for Akkuyu-NPP should be the highest priority on Turkey's agenda.

CHAPTER 6

CONCLUSIONS AND FURTHER RECOMMENDATIONS

The purpose of the following chapter is to conclude the research undertaken for this thesis and to make some recommendations for future studies.

6.1 Major Findings

This research aimed to identify the evacuation zones by developing the superposed nuclear hazard maps using GIS for the hypothetical accident in Akkuyu-NPP. Based on daily superposed nuclear hazard mapping, it observed the dynamic progress of evacuation zones and analyzed the total affected area and population by the ambient dose rate within the zones. The scenario-based analysis helped conclude that meteorological data is a significant factor in identifying evacuation zones. By identifying the evacuation zones and prioritizing the zones by total exposure time, this research detected the level of vulnerability in areas and populations. Thus, this research provided the initial steps of evacuation planning in the emergency preparedness phase for the hypothetical accident in the Akkuyu-NPP.

Although the probability of a severe nuclear accident in the nuclear power plant is regarded as low, the damage that will cause can be extreme. The capacity of ionizing radiation to cause damage to living organisms and the environment led to the world's concern to ensure the safe use of nuclear energy and protect living beings and the environment. Thus, the use of nuclear technologies is subjected to the regulations and standards aiming to control people's radiation exposure and radioactive release to the environment by international and regional regulatory bodies on nuclear energy usage. The standards for nuclear technologies require maintaining an adequate level of planning and preparedness, including countermeasures in case of a nuclear emergency. Evacuation is one of the countermeasures, and evacuation planning has an essential role in nuclear emergency planning in every phase of the disaster cycle.

Within the scope of the research goal, this research estimated a hypothetical accident in INES level 7, depending on the PIEs. The accident started from the Large Break Loss of Coolant (LBLOCA) accident and resulted in in-vessel core melting in the Akkuyu Nuclear Power Plant, causing a massive amount of radiation release. Then, it modeled atmospheric dispersions of Cs-137 and I-131 in the cloud-shine pathway by using the HySPLIT model with a defined source term for LBLOCA at VVER-type reactors and tested this model for the Akkuyu Nuclear Power Plant in Mersin under three different meteorological conditions. The air concentration of radioactive substances requires to be converted to an ambient dose rate with a dose conversion factor to assess the dose affecting humans. Since this research considered only Cs-137 and I-131 as radioactive elements, cloud-shine as a dispersion pathway, and an adult person as a reference person, it used a dose conversion factor providing these criteria to assess the ambient dose rate.

Before performing the actual runs, this research performed several sensitivity analyses to observe the effects of different source term parameters on the ambient dose rate and to decide the parameter values for actual simulations. Additionally, it simulated 52 weeks of the year 2021 with HySPLIT to determine the simulation periods of actual runs. Then, it selected the corresponding week of the month with the low, average, and high wind speed providing the ambient dose distribution from the sea to the inland to be the simulation period: 08-11 February, 15-18 May, and 01-04 December 2021, respectively. Then, it performed the actual simulations for three different meteorological conditions

Thereafter, the research overlapped the cumulative atmospheric dispersion models of Cs-137 and I-131 larger than or equal to 1 mSv/h to define the evacuation zones. 1 mSv/h is the evacuation threshold determined by the IAEA for 4-hour exposure of an unshielded adult reference person to a radioactive plume. Additionally, this research considered the ambient dose rate larger than or equal to 0.5 mSv/h as a threshold for a possible evacuation zone and incorporated it into the analysis. Consequently, it obtained three superposed nuclear hazard maps for each scenario.

Afterward, this research classified the radiation exposure risk into four as ‘low, medium, and high risk’ within the evacuation zone and ‘potential risk zone’ beyond the evacuation zone. This classification is dependent on the total exposure time and helps prioritize the zones. Lastly, it overlapped the predefined risk classification with the geographic distribution of Mersin population data in 2021 and compared the total affected area and population within each scenario to estimate the evacuation demand.

In conclusion, the research provides the initial steps of evacuation planning for the case of Akkuyu-NPP within the provincial boundary of Mersin. This research uses the superposed nuclear hazard mapping indicating the hazard zones based on three different scenarios to reveal the importance of having a comprehensive evacuation plan. In this way, this research provides guidance for emergency responders and decision-makers for the further steps of evacuation planning which help reduce the loss of human lives, minimize radiation exposure, and mitigate the future effects of radiation.

6.2 Recommendations for Future Research

The research presented in this manuscript is the first study in Turkey to determine the potential evacuation zones in case of a nuclear power plant accident. Although the probability of an accident is considered significantly smaller since its newer technology, the modeling study conducted on the Akkuyu-NPP, which is under construction, indicates how many people should be evacuated in case of a severe accident.

Akkuyu is not the only nuclear power plant under construction in Turkey. There is another nuclear power plant planned to be constructed in Sinop. Conducting a similar study with this nuclear power plant can better understand the importance of evacuation studies for nuclear power plants in Turkey.

This research models the atmospheric dispersion and assess the ambient dose by considering only Cs-137 and I-131 as radioactive elements and cloud-shine as a dispersion pathway. Considering all radioactive elements in the radioactive plume with all defined pathways (i.e., inhalation, ground-shine, resuspension, and ingestion) can result in a complete assessment of ambient dose and a more precise determination of evacuation zones.

This study only provides the initial steps of the evacuation planning process. It identifies the evacuation zones, prioritizes them to detect the affected population's vulnerability, and regards only the permanent residents within Mersin province to estimate the evacuation demand. However, in some situations of defined scenarios, it observes that the radioactive plume crossed the provincial boundary of Mersin and the national boundary of Turkey. Future studies might expand the analysis performed in this thesis outside the provincial border of Mersin,

The further development of this research might complete the other steps of evacuation planning, which are: the comprehensive evacuation demand estimation considering the demand profile, identification of the safe zones corresponding to the basic living requirements, estimating the roadway capacity and background traffic within the evacuation zone for optimized evacuation routing and estimating the evacuation time under varying conditions.

6.3 Policy Recommendations for Evacuation Planning in Turkey

Turkey has frequently faced different types of disasters, such as earthquakes, landslides, floods, rockfalls, etc., that lead to human, material, economic, and environmental losses and impacts. Several precautions have been taken for these disasters, such as seismic zones map displaying the earthquake disaster profile of Turkey; however, nuclear hazard maps in case of nuclear power plant emergencies have not been prepared yet. Turkey had attempted to construct a nuclear power plant to satisfy the energy demand within the country for decades. These attempts resulted in two ongoing nuclear power plant construction projects in Akkuyu and Sinop. However, whether Turkey is prepared for nuclear power plants' potential risks and consequences is debatable. The current regulations, plans, and reports explaining the actions and precautions for nuclear power plant emergencies in Turkey do not include detailed and sufficient information about evacuation planning in case of nuclear emergencies. Hence, Mersin and Sinop Governorships should prepare comprehensive radiation emergency action plans involving the evacuation plans in cooperation with the other responsible authorities and service groups defined in NREP as soon as possible to be prepared for the potential severe nuclear power plant accidents. Besides, the responsible authorities should inform the public about the possible risks and consequences of radiation exposure and the emergency actions to be followed in case of nuclear power plant accidents to prevent additional consequences.

REFERENCES

Agrawal, S. K., Chauhan, A., & Mishra, A. (2006). The VVERs at KudanKulam. *Nuclear Engineering and Design*, *236*(7–8), 812–835. https://doi.org/10.1016/j.nucengdes.2005.09.030

Akcay, B. (2009). The case of nuclear energy in Turkey: From chernobyl to akkuyu nuclear power plant. *Energy Sources, Part B: Economics, Planning and Policy*, *4*(4). https://doi.org/10.1080/15567240701621182

Akkuyu Nuclear Power Plant Power Generation Joint Stock Company. (2013). *Site Evaluation Report Volume 1.* (Report No. AKU.C.010.002.HC.0004). https://webim.ndk.gov.tr/file/86f73d30-5d7b-4bf9-822e-61e5e573fc4f

Almeshari, Meshari Yousef (2020). *Assessment of the Potential Radiological Impacts of a Proposed Nuclear Power Plant in Saudi Arabia Based on Atmospheric Releases* (Publication No. 27666112) [Doctoral Dissertation, University of Massachusetts Lowell]. ProQuest Dissertations and Theses Global.

Arnold, D., Gufler, K., Kromp, W., Kromp-Kolb, H., Mraz, G., Seibert, P., Sholly, S., Sutter, P., & Wenisch, A. (2011). FlexRISK – flexible tools for assessment of nuclear risk in Europe. *Air Pollution Modeling and Its Application XXI*, 737–740. https://doi.org/10.1007/978-94-007-1359-8_121

Ayfadopoulou, G., Stamos, I., Mitsakis, E., & Grau, J. M. (2012). Dynamic traffic assignment based evacuation planning for CBD areas. *Procedia - Social and Behavioral Sciences*, *48*, 1078–1087. https://doi.org/10.1016/j.sbspro.2012.06.1084

Bellamy et. al. (2019). *Federal Guidance Report No. 15* (Report No. EPA 402-R-19-002) United States Environmental Protection Agency. https://www.epa.gov/sites/default/files/2019-08/documents/fgr_15_final_508_2019aug02.pdf

Bilgiç, E. (2016). *Atmospheric Dispersion of Radiation Originating from Nuclear Power Plant Accidents* [Master Thesis, Dokuz Eylül University]. Dokuz Eylül University Research Repository.

http://panel.fbe.deu.edu.tr/ArchieveDetail.aspx?Yayin=&Type=Thesis&Ogrenci=2012900069

Bilgiç, E., & Gündüz, O. (2020). Dose and risk estimation of Cs-137 and I-131 released from a hypothetical accident in Akkuyu Nuclear Power Plant. *Journal of Environmental Radioactivity*, *211*. https://doi.org/10.1016/j.jenvrad.2019.106082

Bundesamt für Strahlenschutz. (2020). *What are the effects of radiation?* [online] Available at: <https://www.bfs.de/EN/topics/ion/effect/introduction/introduction.html> [Accessed 24 June 2022].

Centers for Disease Control and Prevention. (2018, April 4). *CDC radiation emergencies*. [online] Available at: https://www.cdc.gov/nceh/radiation/emergencies/isotopes/cesium.htm [Accessed 24 June 2022].

Chen, Yu, Wen, Zhang, Yin, Wu, & Yao. (2019). Pre-evacuation time estimation based emergency evacuation simulation in urban residential communities. *International Journal of Environmental Research and Public Health*, *16*(23), 4599. https://doi.org/10.3390/ijerph16234599

Cova, T. J. (1999). GIS in Emergency Management. *Geographical Information Systems: Principles, Techniques, Applications, and Management*, *Rejeski 1993*.

Cova, T. J., & Johnson, J. P. (2002). Microsimulation of neighborhood evacuations in the urban-wildland interface. *Environment and Planning A*, *34*(12). https://doi.org/10.1068/a34251

Djangmah, J. A. (2013). *Buoyant Gaussian Plume Modeling of Atmospheric Dispersion of Cs-137 Emitted from A Nuclear Reactor* [University of Ghana, MPhil Thesis]. University of Ghana Research Repository. http://ugspace.ug.edu.gh

DOKAY-ÇED Çevre Mühendisliği Ltd. Şti. (2013). *Environmental Impact Assessment Report for Akkuyu Nuclear Power Plant.* Akkuyu Nuclear Power Plant Power Generation Joint Stock Company

Draxler, R. R., & Hess, G. D. (1997). *Description of the Hysplit_4 Modeling System*. NOAA Technical Memorandum ERL ARL-224*,* NOAA Air Resources Laboratory, Silver Spring, MD, 24 pp.

Edwards, P. N. (2010). History of climate modeling. *WIREs Climate Change*, *2*(1), 128–139. https://doi.org/10.1002/wcc.95

Elbaradei, M., Nwogugu, E., & Rames, J. (1995). International law and nuclear energy: Overview of the legal framework - The global legal order for the atom's safe and peaceful uses is grounded on a mix of binding norms and advisory regulations. *IAEA Bulletin*.

Fairuz, A., & Sahadath, M. H. (2020). Assessment of the potential Total Effective Dose (TED) and Ground Deposition (GD) following a hypothetical accident at the proposed Rooppur Nuclear Power Plant. *Applied Radiation and Isotopes*, *158*. https://doi.org/10.1016/j.apradiso.2020.109043

Federal Emergency Management Agency US. (2019). *Planning Considerations: Evacuation and Shelter-in-Place – Guidance for State, Local, Tribal and Territorial Partners.*

Ha-Duong, M., & Journé, V. (2014). Calculating nuclear accident probabilities from empirical frequencies. *Environment Systems and Decisions*, *34*(2), 249–258. https://doi.org/10.1007/s10669-014-9499-0

Hall, D., & Spanton, A. (1999). Meteorological Data and Dispersion Modelling. Clean *Air and Environmental Protection*, *29*(5), 130-137.

Harris, J. B. (2014). *Evacuation and Shelter in Place Modeling for a Release of Uranium Hexafluoride* [Master Thesis, East Tennessee State University]. East Tennessee State University Research Repository. https://dc.etsu.edu/etd/2351

Hsu, Y.-T. (2013). *A generalized operational framework for mass evacuation integrating demand, supply, and disaster characteristics* [Doctoral Dissertation, Purdue

University] Purdue University Research Repository. https://docs.lib.purdue.edu/dissertations/AAI3604881/

IAEA, (1997). *Generic assessment procedures for determining protective actions during a reactor accident* (Report No. TECDOC-955) https://www-pub.iaea.org/MTCD/Publications/PDF/te_955_prn.pdf

IAEA, (2021). *"Country Nuclear Power Profiles, Turkey 2021"*. [online] Available at: <https://cnpp.iaea.org/countryprofiles/Turkey/Turkey.htm> [Accessed 24 June 2022].

IAEA, Vienna (2008). INES: *The International Nuclear and Radiological Event Scale User's Manual,* Non-serial Publications https://www.iaea.org/publications/10508/ines-the-international-nuclear-and-radiological-event-scale-users-manual

IAEA, Vienna (2015). "*The Fukushima Daiichi Accident Report"* (Report No. STI/PUB/1710) https://www-pub.iaea.org/mtcd/publications/pdf/pub1710-reportbythedg-web.pdf

Ichikawa, H. (2016). Obninsk, 1955: The World's First Nuclear Power Plant and "The Atomic Diplomacy" by Soviet Scientists. *Soviet Science and Engineering in the Shadow of the Cold War* (pp. 127-142). Routledge.

Jacquemain, D., Bentaïb, A., Bonneville, H., Cénérino, G., Clément, B., Corenwinder, F., Cranga, M., Ducros, G., Fichot, F., Journeau, C., Koundy, V., Leteinturier, D., Magallon, D., Meignen, R., Monroig, F., Nahas, G., Pichereau, F., Raimond, E., Seiler, J.-M., … Van-Dorsselaere, J.-P. (2015). 5.5. Release of fission products during a core melt accident. *Nuclear Power Reactor Core Melt Accidents: Current State of Knowledge*, 255–299. https://www.irsn.fr/EN/Research/publications-documentation/Scientific-books/Documents/1_LAGEN_chapitre 5.5.pdf

Jafarikia, S., & Feghhi, S. A. H. (2018). Study of in-containment source term behavior for VVER-1000 under LOCA conditions using the IRBURN code system. *Annals of Nuclear Energy*, *112*, 17–29. https://doi.org/10.1016/j.anucene.2017.09.038

Johnson, J. H., & Zeigler, D. J. (1986*). Evacuation planning for Technological Hazard: An emerging imperative. Cities, 3*(2), 148–156. https://doi.org/10.1016/0264-2751(86)90054-5

Krištof, M. (2015). *Postulated Initiating Events Joint ICTP-IAEA Essential Knowledge Workshop on Deterministic Safety Assessment and Engineering Aspects Important to Safety IAEA Safety Assessment Education and Training (SAET) Programme*.

Lauritzen, B., Damkjaer, A., Baeverstam, U., Naadland Holo, E., & Sinkko, K. (1997). Operational intervention levels in a nuclear emergency, general concepts, and a probabilistic approach (No. NKS/EKO--3 (EN). 3 (97) TR-1). Nordisk Kernesikkerhedsforskning.

Leelőssy, Á., Lagzi, I., Kovács, A., & Mészáros, R. (2018). A review of numerical models to predict the atmospheric dispersion of radionuclides. In *Journal of Environmental Radioactivity* (Vol. 182, pp. 20–33). Elsevier Ltd. https://doi.org/10.1016/j.jenvrad.2017.11.009

Likhtarev, I.A., Chumack, V.V., Repin, V.S., 1994. Analysis of the effectiveness of emergency countermeasures in the 30-km zone during the early phase of the Chernobyl accident. *The Radiation Safety Journal Health Physics*, 67, 541–544. https://doi.org/10.1097/00004032-199411000-00010

Malešič, M., Prezelj, I., Juvan, J., Polič, M., & Uhan, S. (2015). Evacuation in the event of a nuclear disaster: Planned activity or improvisation? *International Journal of Disaster Risk Reduction*, *12*, 102–111. https://doi.org/10.1016/j.ijdrr.2014.12.005

Matheron, P., Chapuliot, S., Nicolas, L., Koundy, V., & Caroli, C. (2012). Characterization of PWR vessel steel tearing under severe accident condition temperatures. *Nuclear Engineering and Design*, *242*, 124–133. https://doi.org/10.1016/j.nucengdes.2011.10.046

Menzel, H. G., & Harrison, J. (2012). Effective dose: a radiation protection quantity. *Annals of the ICRP*, *41*(3–4), 117–123. https://doi.org/10.1016/J.ICRP.2012.06.022

Miller, I. M. (2015). *Integrating Geographic Information Systems with The Level 3 Probabilistic Risk Assessment of Nuclear Power Plants to Advance Modeling of Socio-Technical Infrastructure in Emergency Response Applications.* {Master Thesis, University of Illinois at Urbana-Champaign]. University of Illinois at Urbana-Champaign Research Repository. https://www.ideals.illinois.edu/

Ministry of Environment, Government of Japan. (2019). "*Exposure Modes and Effects*". [online] Available at: <https://www.env.go.jp/en/chemi/rhm/basic-info/1st/03-01-01.html> [Accessed 24 June 2022].

Moynihan, G. P., & Fonseca, D. J. (2016). Design of an evacuation demand forecasting module for Hurricane Planning Applications. *Journal of Transportation Technologies*, *06*(05), 257–276. https://doi.org/10.4236/jtts.2016.65024

Ohba, T., Tanigawa, K., & Liutsko, L. (2021). Evacuation after a nuclear accident: Critical reviews of past nuclear accidents and proposal for future planning. *Environment International*, *148*, 106379. https://doi.org/10.1016/j.envint.2021.106379

SCENIHR. (2012). "*Health effects of security scanners for passenger screening (based on X-raytechnology)*". [online] Available at: http://ec.europa.eu/health/scientific_committees/emerging/members_wg/index_en.htm [Accessed 24 June 2022].

Schaefer, K.E., 2019. *A Holistic Methodology for Large-Scale Evacuation Routing*. (Publication No. 27670651) [Doctoral Dissertation, Saint Louis University]. ProQuest Dissertations and Theses Global.

Shahabi, K. (2012). *Arcuser.* Out of Harm's Way: Enabling intelligent location-based evacuation routing. Retrieved July 14, 2022, from https://www.esri.com/news/arcuser/0612/out-of-harms-way.html

Smith JS, Fisher JH. Three Mile Island: The Silent Disaster. *JAMA*. 1981;245(16):1656–1659. doi:10.1001/jama.1981.03310410034023

Soffer L., Burson B. S., Ferrel M. C., Lee Y. R., Ridgely N. J. (1995) *Accident Source Terms for Light-Water Nuclear Power Plants* (Report No. NUREG-1465). United States Nuclear Regulatory Commission. https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1465/index.html#pub-info

Soffer, Y., Schwartz, D., Goldberg, A., Henenfeld, M., Bar-Dayan, Y., 2008. Population evacuations in industrial accidents: a review of the literature about four major events. *Prehospital Disaster Med. 23*, 276–281. DOI: https://doi.org/10.1017/S1049023X00065006

Southworth, F. (1991). Regional Evacuation Modeling: A State-of-the-Art Review. *Oak Ridge National Labs*, ORNL/TM-11740. https://doi.org/10.2172/814579

Sovacool, B. K. (2010). A critical evaluation of nuclear power and renewable electricity in Asia. *Journal of Contemporary Asia*, *40*(3), 369–400. https://doi.org/10.1080/00472331003798350

Stein, A. F., Draxler, R. R., Rolph, G. D., Stunder, B. J. B., Cohen, M. D., & Ngan, F. (2015). Noaa's hysplit atmospheric transport and dispersion modeling system. In *Bulletin of the American Meteorological Society* (Vol. 96, Issue 12, pp. 2059–2077). American Meteorological Society. https://doi.org/10.1175/BAMS-D-14-00110.1

Stepanov, A., & Smith, J. M. G. (2009). Multi-objective evacuation routing in Transportation Networks. *European Journal of Operational Research*, *198*(2), 435–446. https://doi.org/10.1016/j.ejor.2008.08.025

Szczepanik, D. M., Stachlewska, I. S., Tetoni, E., & Althausen, D. (2021). Properties of Saharan dust versus local urban dust—a case study. *Earth and Space Science*, *8*(12). https://doi.org/10.1029/2021ea001816

Tanigawa, K., Hosoi, Y., Hirohashi, N., Iwasaki, Y., Kamiya, K., 2012. Loss of life after evacuation: lessons learned from the Fukushima accident. *Lancet 379*, 889–891. https://doi.org/10.1016/S0140-6736(12)60384-5

Turkish Atomic Energy Authority. (2013). *Site Evaluation Report on Updated Site Report for Akkuyu Nuclear Power Plant Revision 2* (Report No. ANS.GDR01E.USR)

Department of Nuclear Safety Turkish. https://webim.ndk.gov.tr/file/03bcd23a-12ee-444c-80cf-ae6ed0b64776

Ünver, Ö. (2003). *A Modelling Study for The Health Risk Posed by Nuclear Power Plant in Bulgaria at Different Parts of Turkey* [Master thesis, Middle East Technical University]. Middle East Technical University Research Repository. http://etd.lib.metu.edu.tr/upload/729053/index.pdf

Urbanik, T. (2000). Evacuation time estimates for nuclear power plants. *Journal of Hazardous Materials*, *75*(2-3), 165–180. https://doi.org/10.1016/s0304-3894(00)00178-3

US EPA. 2022. *Air Quality Dispersion Modeling | US EPA*. [online] Available at: <https://www.epa.gov/scram/air-quality-dispersion-modeling> [Accessed 24 June 2022].

Wessells, C. (2012, March 20). *Cesium-137: A deadly hazard*. Retrieved February 15, 2022, from http://large.stanford.edu/courses/2012/ph241/wessells1/

World Nuclear Association. (2022). *History of Nuclear Energy - World Nuclear Association*. [online] Available at: <https://www.world-nuclear.org/information-library/current-and-future-generation/outline-history-of-nuclear-energy.aspx> [Accessed 24 June 2022].

Xie, K., Ozbay, K., Zhu, Y., & Yang, H. (2017). Evacuation zone modeling under climate change: A data-driven method. *Journal of Infrastructure Systems*, 23(4). https://doi.org/10.1061/(asce)is.1943-555x.0000369

Zibulewsky, J. (2001). Defining disaster: the emergency department perspective. In *BUMC PROCEEDINGS* (Vol. 14).

APPENDICES

A. Dose Conversion Factors

Table A.1 *Dose Conversion Factors by Federal Guidance Report No. 15, p.200*

	Reference Person Coefficients (Sv Bq^{-1} s^{-1} m^3)					
Nuclide	Newborn	1-yr-old	5-yr-old	10-yr-old	15-yr-old	Adult
Cs-121m	7.64E-14	7.20E-14	6.81E-14	6.49E-14	5.97E-14	5.72E-14
Cs-123	6.79E-14	6.40E-14	6.07E-14	5.77E-14	5.31E-14	5.08E-14
Cs-124	7.97E-14	7.54E-14	7.16E-14	6.82E-14	6.30E-14	6.04E-14
Cs-125	4.55E-14	4.29E-14	4.07E-14	3.87E-14	3.56E-14	3.41E-14
Cs-126	7.46E-14	7.05E-14	6.69E-14	6.36E-14	5.86E-14	5.62E-14
Cs-127	2.48E-14	2.31E-14	2.17E-14	2.06E-14	1.89E-14	1.81E-14
Cs-128	5.63E-14	5.31E-14	5.04E-14	4.80E-14	4.41E-14	4.22E-14
Cs-129	1.53E-14	1.41E-14	1.33E-14	1.26E-14	1.15E-14	1.10E-14
Cs-130	3.07E-14	2.89E-14	2.75E-14	2.61E-14	2.40E-14	2.30E-14
Cs-130m	3.02E-15	2.61E-15	2.31E-15	2.20E-15	1.83E-15	1.69E-15
Cs-131	4.89E-16	3.58E-16	2.94E-16	2.72E-16	2.01E-16	1.79E-16
Cs-132	4.15E-14	3.93E-14	3.72E-14	3.54E-14	3.26E-14	3.11E-14
Cs-134	9.25E-14	8.82E-14	8.36E-14	7.95E-14	7.33E-14	7.02E-14
Cs-134m	1.20E-15	1.04E-15	9.54E-16	9.03E-16	7.85E-16	7.56E-16
Cs-135	1.47E-16	1.43E-16	1.36E-16	1.31E-16	1.23E-16	1.19E-16
Cs-135m	9.48E-14	9.09E-14	8.60E-14	8.18E-14	7.56E-14	7.24E-14
Cs-136	1.27E-13	1.22E-13	1.15E-13	1.09E-13	1.01E-13	9.71E-14
Cs-137	4.76E-16	4.62E-16	4.42E-16	4.26E-16	4.02E-16	3.89E-16
Cs-138	1.48E-13	1.43E-13	1.36E-13	1.30E-13	1.22E-13	1.18E-13
Cs-138m	2.55E-14	2.43E-14	2.31E-14	2.20E-14	2.05E-14	1.97E-14
Cs-139	2.68E-14	2.60E-14	2.48E-14	2.38E-14	2.24E-14	2.16E-14
Cs-140	1.19E-13	1.14E-13	1.09E-13	1.05E-13	9.88E-14	9.52E-14
Barium						
Ba-124	3.36E-14	3.17E-14	2.99E-14	2.85E-14	2.62E-14	2.51E-14
Ba-126	3.36E-14	3.18E-14	2.99E-14	2.85E-14	2.63E-14	2.52E-14
Ba-127	4.50E-14	4.24E-14	4.02E-14	3.83E-14	3.53E-14	3.38E-14
Ba-128	3.05E-15	2.72E-15	2.47E-15	2.34E-15	2.09E-15	2.00E-15
Ba-129	1.94E-14	1.82E-14	1.72E-14	1.64E-14	1.51E-14	1.44E-14
Ba-129m	9.33E-14	8.88E-14	8.40E-14	8.01E-14	7.41E-14	7.11E-14
Ba-131	2.70E-14	2.51E-14	2.36E-14	2.24E-14	2.04E-14	1.96E-14
Ba-131m	4.00E-15	3.49E-15	3.20E-15	2.99E-15	2.62E-15	2.53E-15
Ba-133	2.22E-14	2.04E-14	1.90E-14	1.80E-14	1.63E-14	1.56E-14
Ba-133m	3.48E-15	3.15E-15	2.89E-15	2.74E-15	2.48E-15	2.38E-15
Ba-135m	3.03E-15	2.73E-15	2.50E-15	2.38E-15	2.15E-15	2.05E-15
Ba-137m	3.52E-14	3.35E-14	3.17E-14	3.02E-14	2.78E-14	2.66E-14
Ba-139	6.33E-15	6.00E-15	5.67E-15	5.45E-15	5.05E-15	4.88E-15
Ba-140	1.14E-14	1.07E-14	1.01E-14	9.62E-15	8.82E-15	8.45E-15
Ba-141	5.92E-14	5.62E-14	5.30E-14	5.06E-14	4.69E-14	4.50E-14
Ba-142	6.34E-14	6.07E-14	5.73E-14	5.46E-14	5.06E-14	4.85E-14
Lanthanum						
La-128	1.74E-13	1.66E-13	1.57E-13	1.50E-13	1.38E-13	1.33E-13
La-129	5.65E-14	5.31E-14	5.02E-14	4.77E-14	4.38E-14	4.20E-14
La-130	1.38E-13	1.31E-13	1.24E-13	1.19E-13	1.10E-13	1.05E-13
La-131	3.90E-14	3.64E-14	3.43E-14	3.26E-14	2.99E-14	2.86E-14
La-132	1.21E-13	1.16E-13	1.10E-13	1.05E-13	9.79E-14	9.40E-14
La-132m	3.93E-14	3.70E-14	3.49E-14	3.32E-14	3.04E-14	2.91E-14

Table A.2 *Dose Conversion Factors by Federal Guidance Report No. 15, p.199*

Nuclide	Reference Person Coefficients (Sv Bq^{-1} s^{-1} m^{3})					
	Newborn	1-yr-old	5-yr-old	10-yr-old	15-yr-old	Adult
Te-131m	8.67E-14	8.29E-14	7.84E-14	7.48E-14	6.92E-14	6.64E-14
Te-132	1.31E-14	1.19E-14	1.09E-14	1.04E-14	9.42E-15	9.04E-15
Te-133	7.46E-14	7.12E-14	6.75E-14	6.45E-14	6.01E-14	5.77E-14
Te-133m	1.12E-13	1.07E-13	1.02E-13	9.69E-14	8.99E-14	8.62E-14
Te-134	5.16E-14	4.87E-14	4.58E-14	4.36E-14	4.00E-14	3.83E-14
Iodine						
I-118	1.31E-13	1.24E-13	1.18E-13	1.12E-13	1.04E-13	9.95E-14
I-118m	2.27E-13	2.16E-13	2.05E-13	1.95E-13	1.80E-13	1.73E-13
I-119	5.55E-14	5.21E-14	4.91E-14	4.67E-14	4.29E-14	4.11E-14
I-120	1.66E-13	1.59E-13	1.52E-13	1.45E-13	1.36E-13	1.30E-13
I-120m	2.14E-13	2.04E-13	1.94E-13	1.85E-13	1.71E-13	1.64E-13
I-121	2.30E-14	2.14E-14	2.00E-14	1.90E-14	1.74E-14	1.66E-14
I-122	6.18E-14	5.84E-14	5.55E-14	5.28E-14	4.86E-14	4.65E-14
I-123	9.20E-15	8.32E-15	7.73E-15	7.40E-15	6.58E-15	6.35E-15
I-124	6.64E-14	6.32E-14	6.02E-14	5.74E-14	5.32E-14	5.10E-14
I-125	7.97E-16	5.68E-16	4.71E-16	4.35E-16	3.14E-16	2.78E-16
I-126	2.58E-14	2.43E-14	2.30E-14	2.19E-14	2.01E-14	1.92E-14
I-128	6.91E-15	6.58E-15	6.25E-15	5.97E-15	5.54E-15	5.33E-15
I-129	6.18E-16	4.70E-16	3.93E-16	3.64E-16	2.81E-16	2.54E-16
I-130	1.27E-13	1.21E-13	1.15E-13	1.09E-13	1.00E-13	9.61E-14
I-130m	6.90E-15	6.52E-15	6.19E-15	5.89E-15	5.43E-15	5.20E-15
I-131	2.31E-14	2.15E-14	2.02E-14	1.92E-14	1.76E-14	1.69E-14
I-132	1.36E-13	1.30E-13	1.23E-13	1.18E-13	1.09E-13	1.04E-13
I-132m	2.00E-14	1.89E-14	1.79E-14	1.70E-14	1.56E-14	1.50E-14
I-133	3.76E-14	3.56E-14	3.38E-14	3.21E-14	2.96E-14	2.83E-14
I-134	1.57E-13	1.50E-13	1.42E-13	1.36E-13	1.26E-13	1.21E-13
I-134m	1.63E-14	1.50E-14	1.39E-14	1.32E-14	1.21E-14	1.16E-14
I-135	9.61E-14	9.26E-14	8.81E-14	8.43E-14	7.88E-14	7.58E-14
Xenon						
Xe-120	2.21E-14	2.07E-14	1.94E-14	1.85E-14	1.69E-14	1.61E-14
Xe-121	9.03E-14	8.60E-14	8.20E-14	7.84E-14	7.31E-14	7.02E-14
Xe-122	3.12E-15	2.79E-15	2.58E-15	2.45E-15	2.18E-15	2.08E-15
Xe-123	3.78E-14	3.57E-14	3.37E-14	3.22E-14	2.97E-14	2.85E-14
Xe-125	1.49E-14	1.37E-14	1.26E-14	1.20E-14	1.09E-14	1.05E-14
Xe-127	1.56E-14	1.43E-14	1.32E-14	1.26E-14	1.14E-14	1.09E-14
Xe-127m	9.39E-15	8.42E-15	7.79E-15	7.41E-15	6.59E-15	6.38E-15
Xe-129m	1.54E-15	1.25E-15	1.09E-15	1.02E-15	8.47E-16	7.91E-16
Xe-131m	5.95E-16	4.81E-16	4.21E-16	3.98E-16	3.29E-16	3.08E-16
Xe-133	2.18E-15	1.90E-15	1.68E-15	1.61E-15	1.34E-15	1.22E-15
Xe-133m	1.85E-15	1.64E-15	1.49E-15	1.41E-15	1.26E-15	1.21E-15
Xe-135	1.56E-14	1.45E-14	1.34E-14	1.28E-14	1.17E-14	1.13E-14
Xe-135m	2.50E-14	2.35E-14	2.23E-14	2.12E-14	1.95E-14	1.86E-14
Xe-137	1.99E-14	1.91E-14	1.81E-14	1.74E-14	1.62E-14	1.56E-14
Xe-138	7.03E-14	6.74E-14	6.43E-14	6.17E-14	5.79E-14	5.58E-14
Cesium						
Cs-121	7.83E-14	7.39E-14	7.01E-14	6.67E-14	6.15E-14	5.89E-14

B. Atmospheric Dispersion Model Results

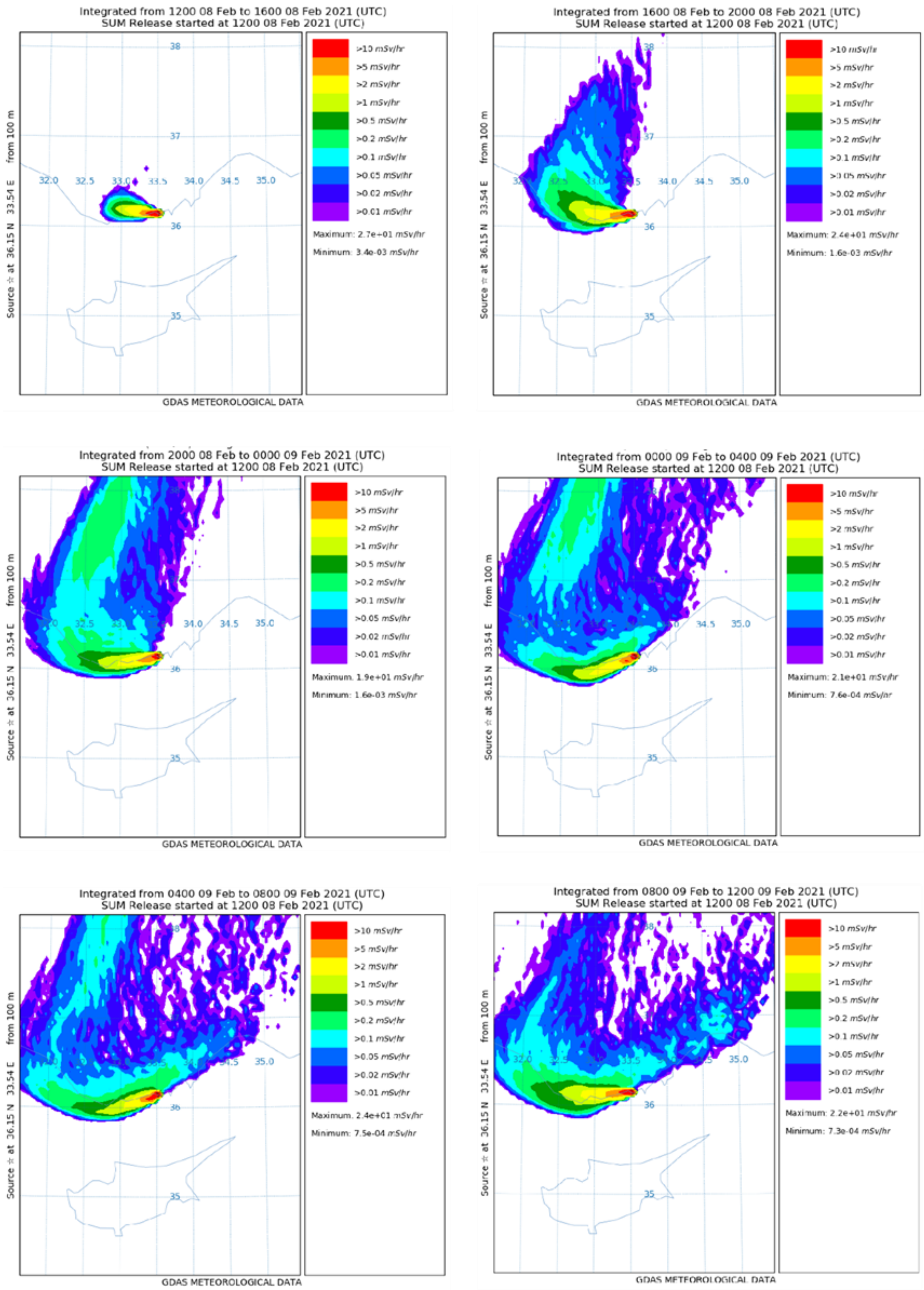

Figure B.1. Atmospheric dispersion model results of HySPLIT: Scenario 1 Day 1

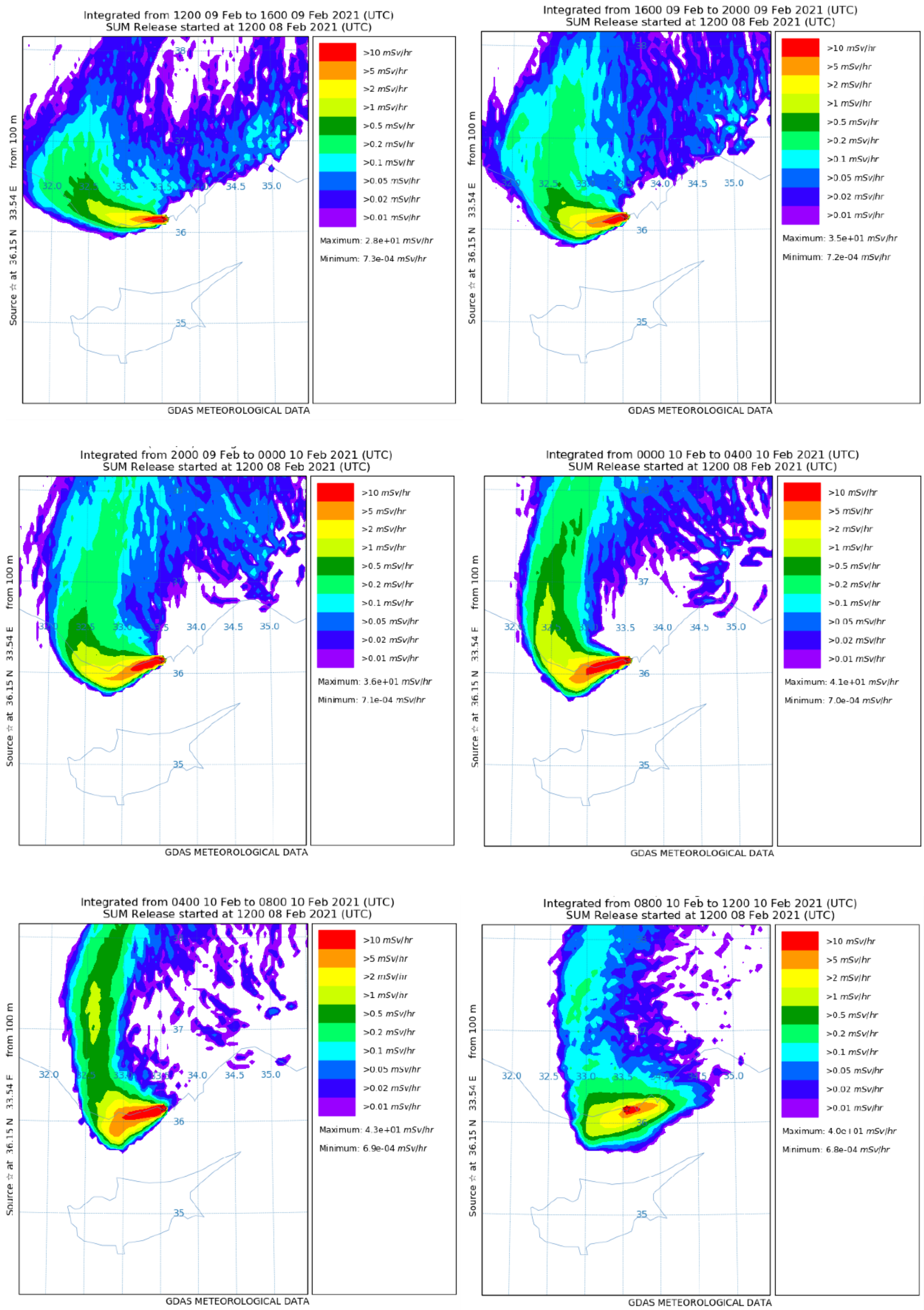

Figure B.2. Atmospheric dispersion model results of HySPLIT: Scenario 1 Day 2

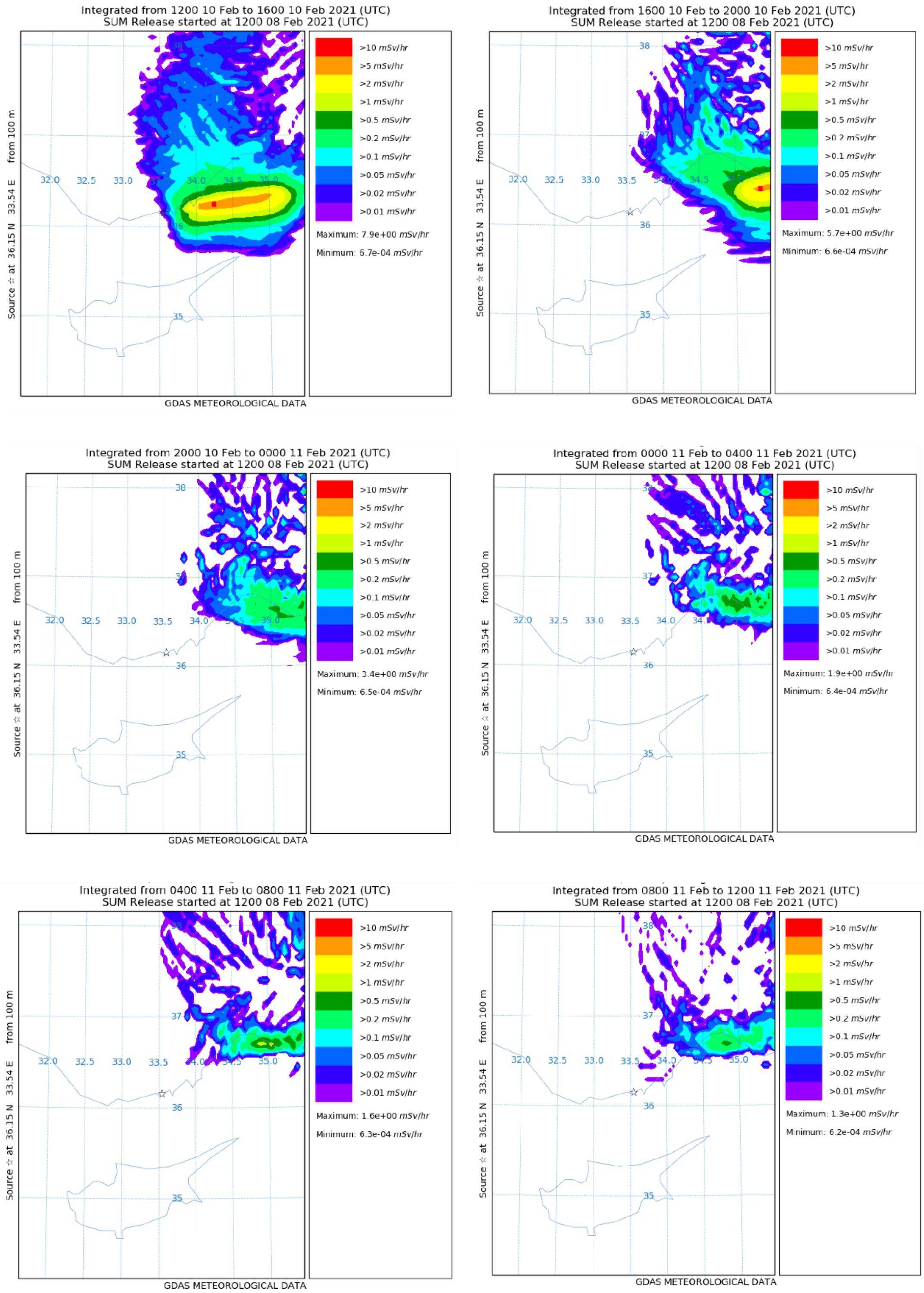

Figure B.3. Atmospheric dispersion model results of HySPLIT: Scenario 1 Day 3

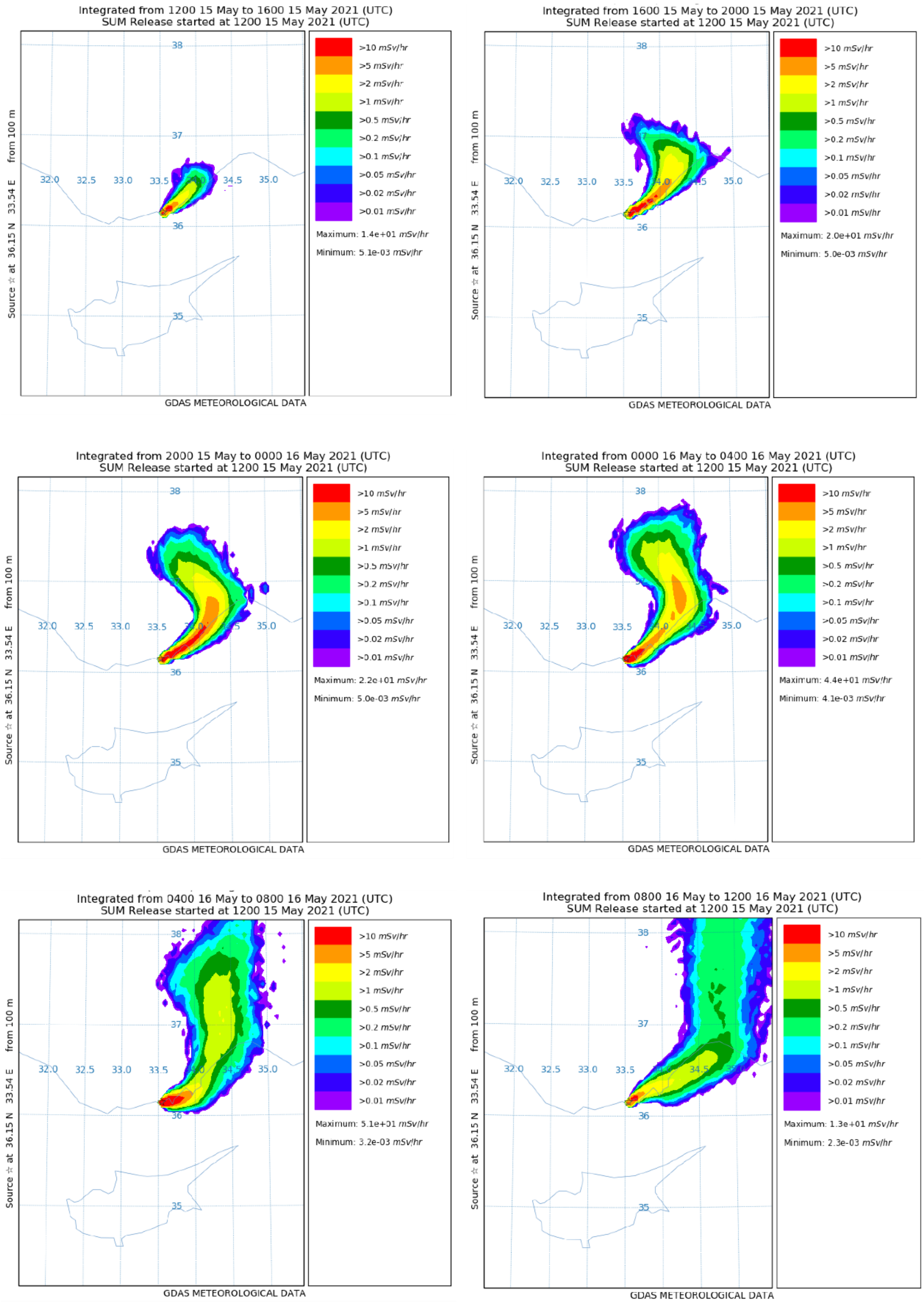

Figure B.4. Atmospheric dispersion model results of HySPLIT: Scenario 2 Day 1

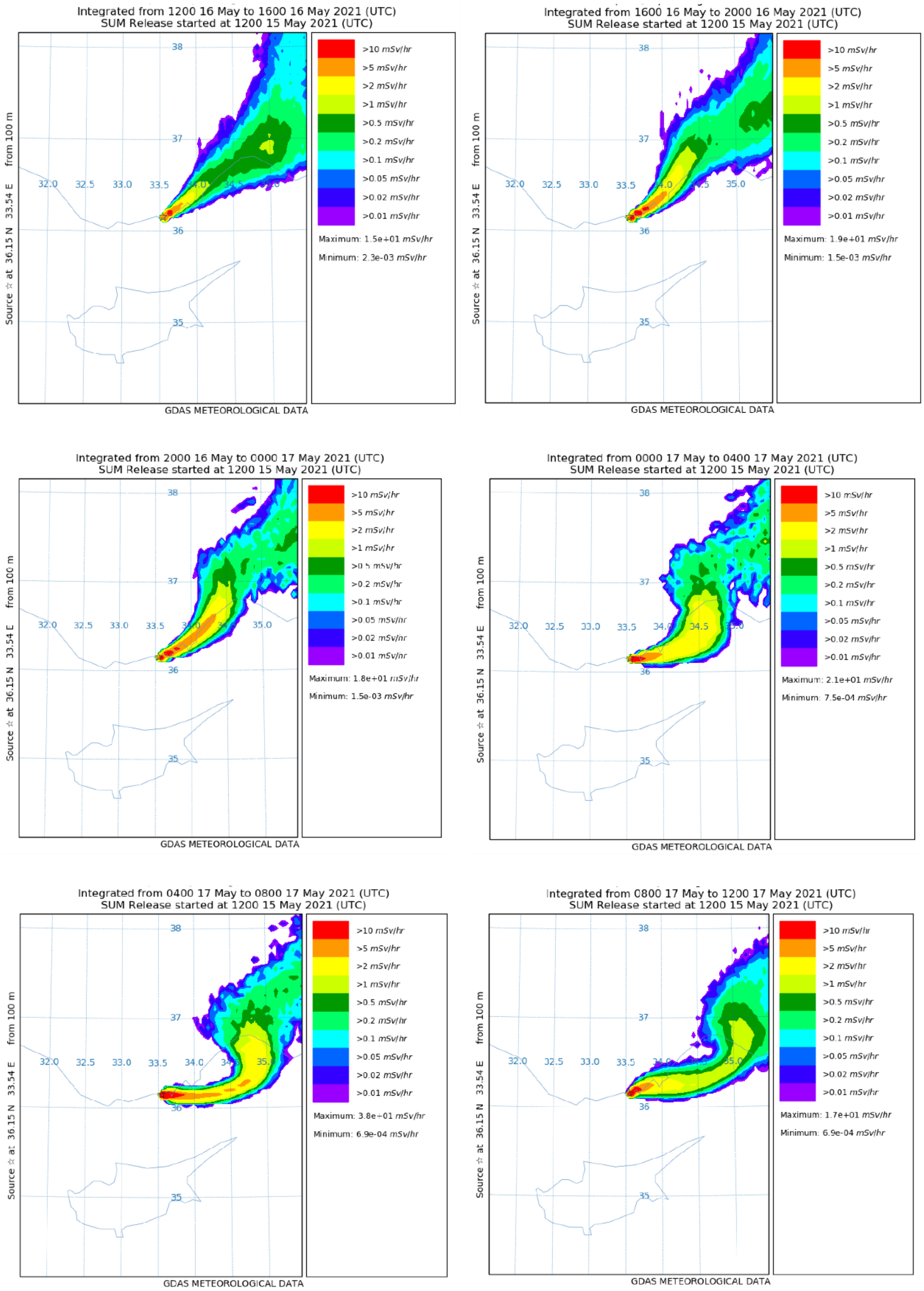

Figure B.5. Atmospheric dispersion model results of HySPLIT: Scenario 2 Day 2

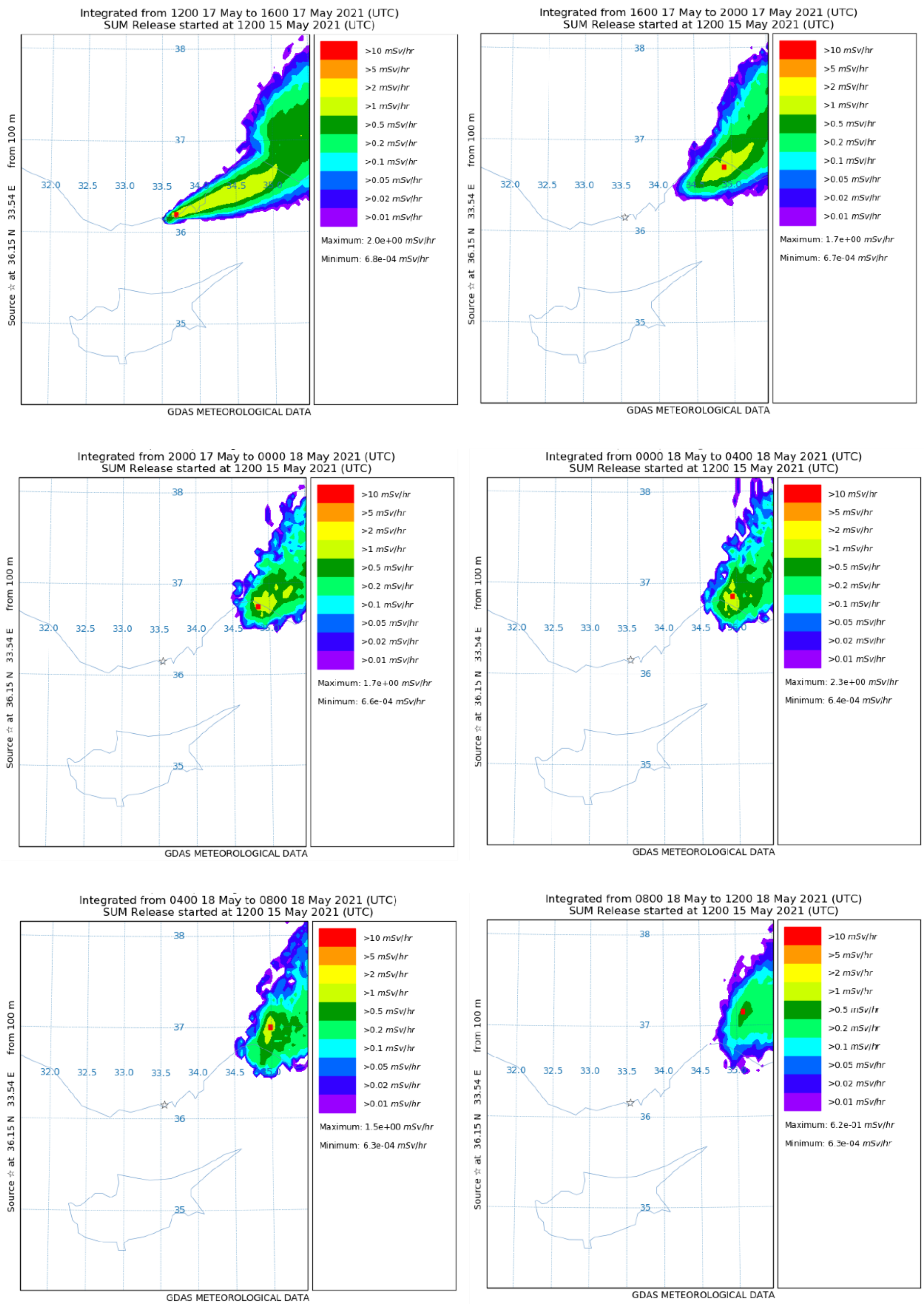

Figure B.6. Atmospheric dispersion model results of HySPLIT: Scenario 2 Day 3

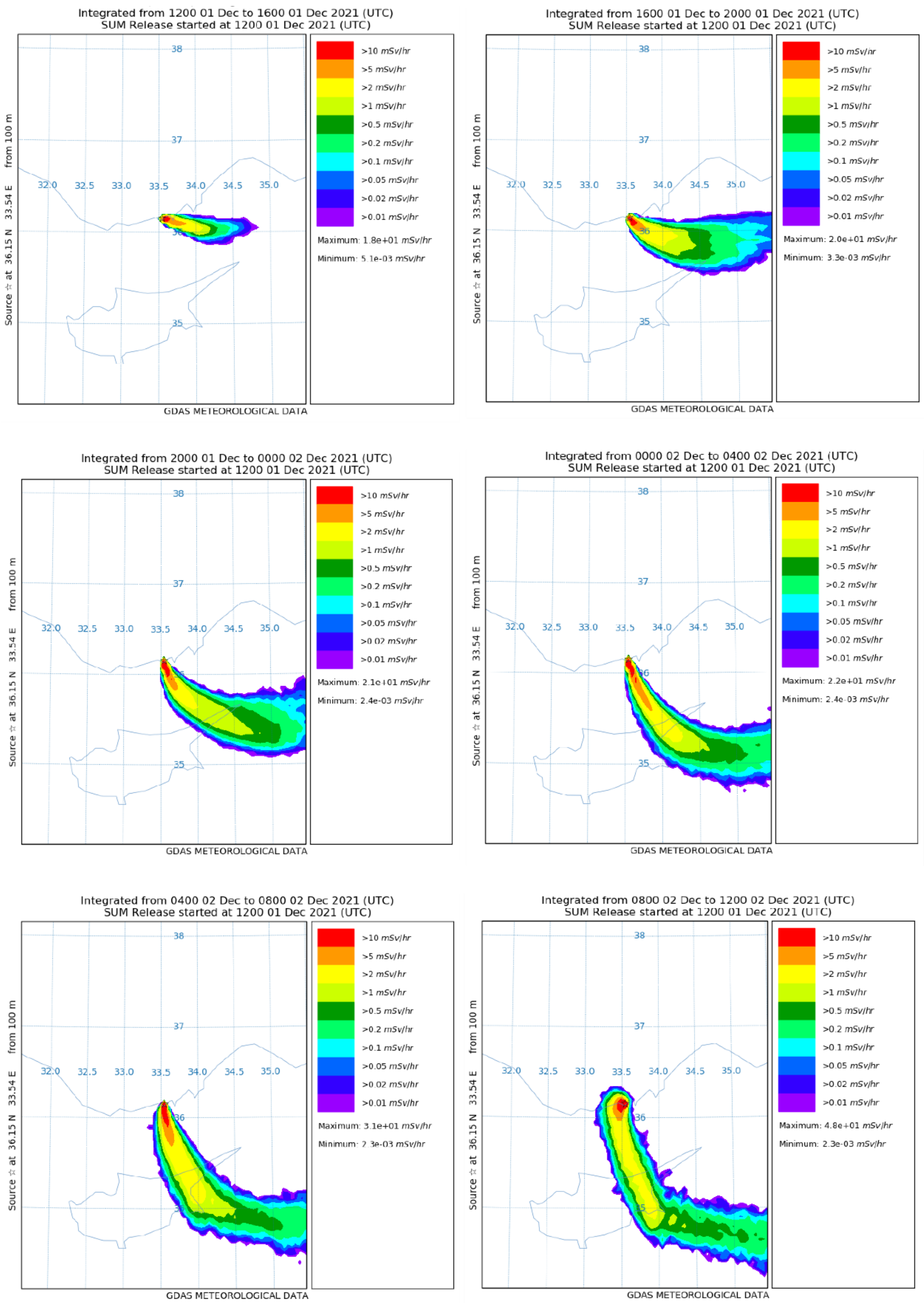

Figure B.7. Atmospheric dispersion model results of HySPLIT: Scenario 3 Day 1

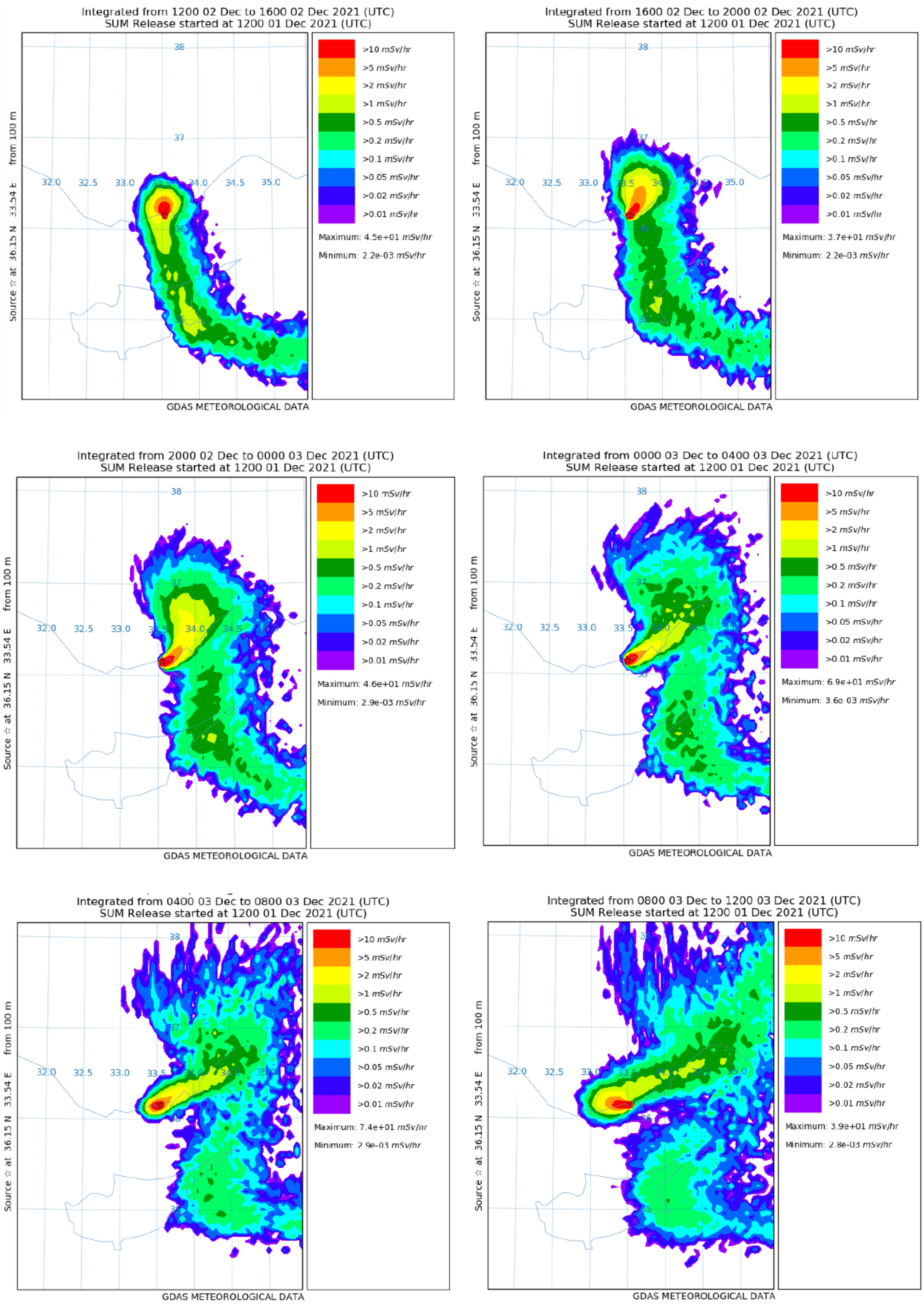

Figure B.8. Atmospheric dispersion model results of HySPLIT: Scenario 3 Day 2

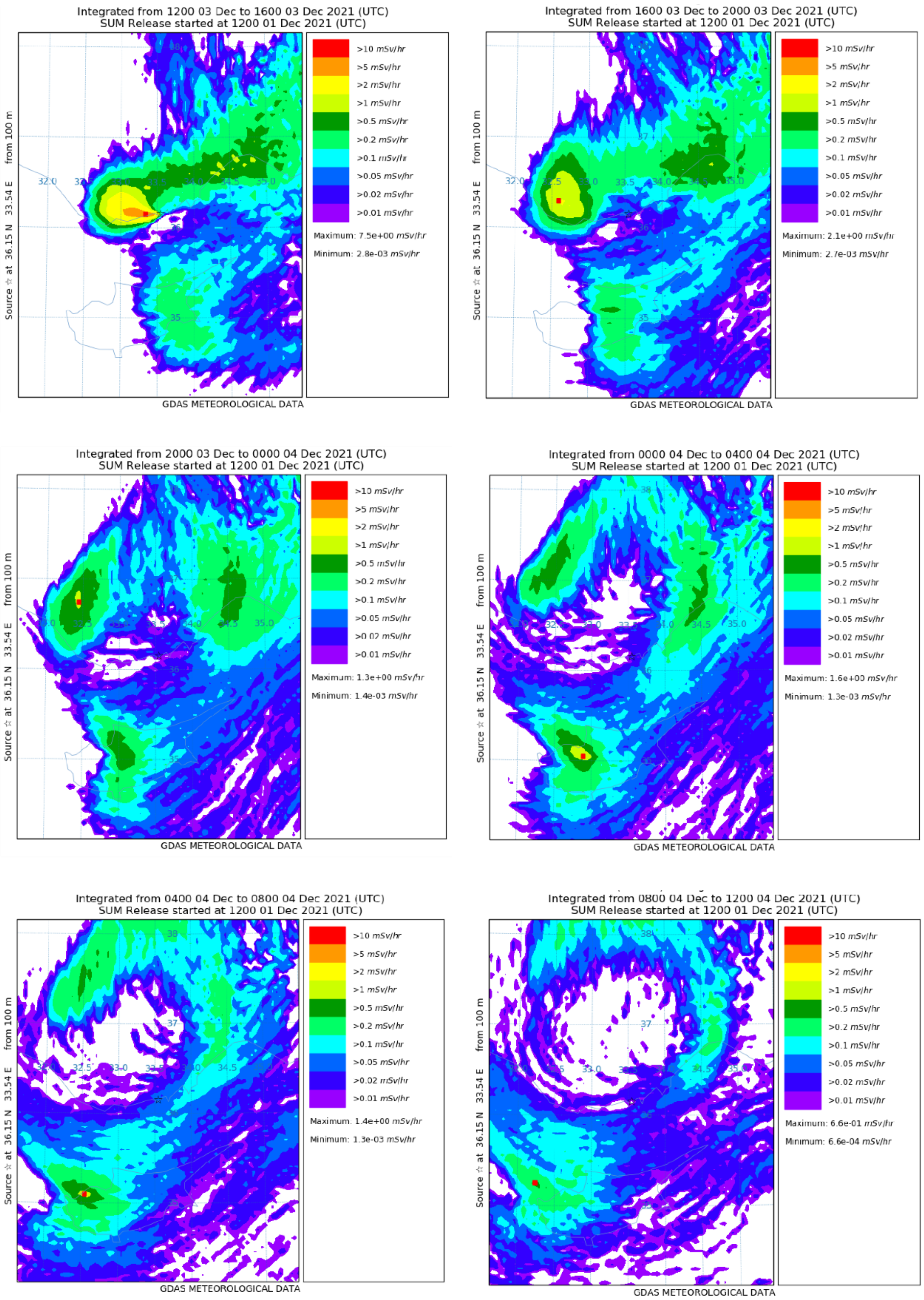

Figure B.9. Atmospheric dispersion model results of HySPLIT: Scenario 3 Day 3