ENHANCING RADIOLOGICAL DISASTER RESPONSE MANUALS IN THE REPUBLIC OF KOREA THROUGH A RESILIENCE ENGINEERING-INFORMED SURVEY

by

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This study evaluates current radiological disaster response manuals for resident protection near nuclear power plants in the Republic of Korea, a crucial aspect of radiological emergency preparedness. The research identifies strategies for improvement based on data collected from emergency responders in nuclear power plant-adjacent regions using a survey questionnaire grounded in resilience engineering principles. Key focus areas include environmental and social factor analysis, manual standardization, shelter optimization and scenario development for vulnerable groups. The study recommends redistributing responsibilities across government levels, improving communication channels, maintaining expertise in emergency preparedness, and providing local governments with adequate financial and human resources to implement these enhancements effectively.

Key words: radiological emergency response manual, radiological emergency preparedness, survey, resilience engineering, nuclear power plant

INTRODUCTION

When a radiological disaster occurs, its impact can extend beyond the regional level and have long-term effects on a national scale. In the aftermath of the Fukushima nuclear power plant (NPP) accident, efforts to enhance disaster response in the nuclear and radiation fields have significantly intensified [1, 2]. The government of the Republic of Korea (ROK) has similarly invested in developing and strengthening systems to monitor NPP and protect residents living near these facilities, in the event of an accident. Timely monitoring of the accident's progression and the implementation of appropriate measures to prevent, or minimize harm to residents and property, are crucial for ensuring public safety. Therefore, local and metropolitan governments situated near NPP must be adequately prepared for radiological disasters by establishing and continuously updating radiological disaster response manuals and systems [3].

It is essential to understand and reflect the characteristics of radiological disasters in improving response manuals. Typically, radiological disasters have long-lasting effects and require an extended recovery period to restore the environment to its pre-disaster state. Additionally, the impact zone of a radiological disaster is significantly wider than that of other disasters. For instance, radioactive materials released during an incident can be carried over long distances by wind and deposited gradually through rainfall or snowfall, leading to contamination of food and water supplies in a broader and more severe impact. Consequently, the extent of the affected area in a radiological disaster is often dictated by the reach of the radioactive plume [4-6].

The Fukushima NPP accident exemplifies these characteristics of radiological disasters. Approximately 900 petabecquerels (PBq) of radioactive substances were released during this incident, which is equivalent to about one-sixth of the emissions from the Chernobyl disaster. An assessment of cumulative external radiation exposure during the first four months following the accident, focusing on around 14 000 residents, revealed that approximately 0.7 % of these residents were exposed to radiation levels exceeding 10 mSv, while 42.3 % received less than 10 mSv [7].

Furthermore, the situation was exacerbated by issues related to miscommunication and decision-making. Despite notifications from the government and local authorities regarding the accident and the dispersal of radioactive materials, many residents remained uninformed. As the crisis intensified, evacuation details and other critical information were frequently updated, of-

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ten without sufficient explanation, leaving many residents unaware of the true severity of the situation. As a result, 146 520 residents evacuated in response to government orders, yet most did so with limited information and only essential items [7, 8].

The Fukushima incident highlights the importance of timely and accurate information in managing evacuations effectively. The absence of reliable information led to multiple relocations for residents and, in some cases, exposure to radiation. Therefore, it is crucial to establish a comprehensive and structured system for collecting, analyzing, and disseminating information during nuclear disasters. This system should account for factors such as weather, topography, population distribution, and road conditions, enabling decision-makers to make informed decisions swiftly, based on reliable data.

Our previous research has extensively explored various aspects of radiological disaster management, providing a foundation for the present study [9]. In earlier studies, we analyzed the Fukushima NPP accident and its aftermath, emphasizing the critical role of timely and accurate information in effective evacuation and disaster response. Additionally, we examined the integration and inconsistencies within domestic legal frameworks governing radiological emergencies. These investigations have not only deepened our understanding of the complexities involved in nuclear disaster management but also refined our methodological approaches for assessing emergency response systems. This strong research foundation supports our expertise in the field and informs the strategies proposed in this study.

The purpose of this study is to evaluate the current radiological disaster response manuals for protecting residents (hereafter referred to as the *resident protection manual*) near NPP in the ROK and to identify areas requiring improvement by conducting a survey of the personnel responsible for implementing these responses. The survey questionnaire was designed by considering not only the principles of resilience engineering but also the characteristics of radiological disasters, aiming to gather insights on enhancing these areas and providing specific guidance for improving the manual.

METHODOLOGY

To improve the radiological disaster response manual, we aimed to design survey questions and conduct a survey targeting personnel currently engaged in radiological disaster response work. For this purpose, this study analyzed the characteristics of radiological disasters and examined them from the perspective of resilience engineering to derive common core keywords. Based on these keywords, we designed survey questions. The survey was then distributed directly to individuals performing disaster response duties, allowing them to respond without time constraints. The analysis procedure was carried out in the sequence shown in fig. 1.

Review of the current radiological disaster response system

In disaster situations, a clear manual outlining appropriate actions is essential to protect residents. First, developing a local radiation disaster prevention

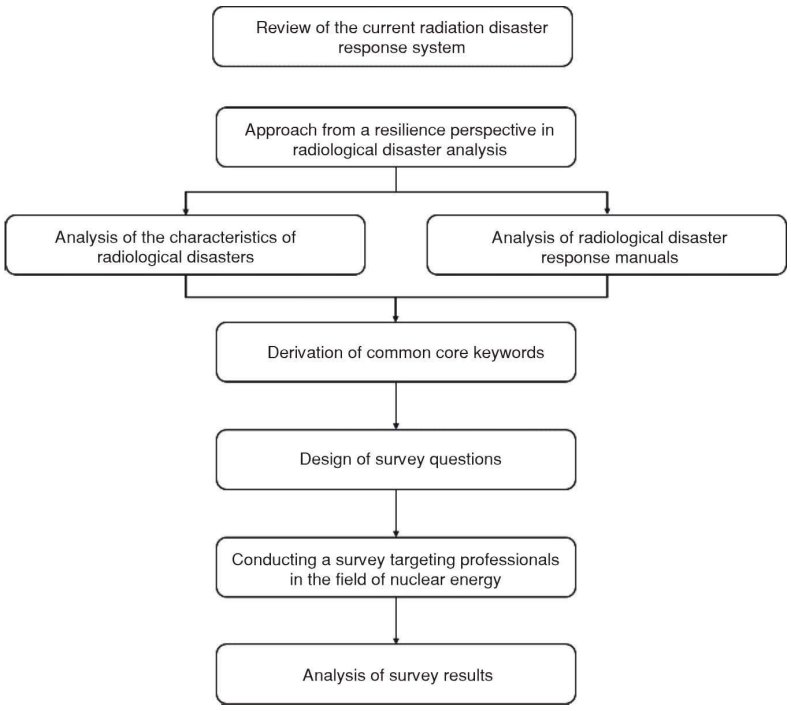

Figure 1. Framework for analyzing and designing survey questions in radiological disaster preparedness

plan and on-site action manual tailored to the region's unique characteristics, is crucial for effective nuclear safety. To achieve this, we reviewed the manuals of each local government and identified several areas for improvement.

However, our review revealed that limited human resources often hinder local governments from developing plans that accurately reflect their area's distinct features. Critical decisions to protect residents must be made early in an incident, yet prompt and precise decision-making is challenging when information is scarce.

Existing shelters designated for temporary stays and public gatherings during disasters are intended to provide essential resources like electricity and water. However, in the ROK, these shelters are insufficiently prepared for the unique challenges posed by radiological disasters, as they primarily focus on temporary gathering rather than addressing the specific needs of residents. Additionally, some shelters are located in areas vulnerable to radioactive plume directions, potentially putting evacuees at risk [10]. To reduce the impact on residents during radiological disasters, a comprehensive assessment of the areas surrounding NPP, considering factors like wind direction and road conditions, is essential. Given the seasonal and daily variations in weather patterns, regularly reevaluating designated shelters is crucial.

Furthermore, to prevent confusion during radiological disasters, it is vital to clearly identify the personnel responsible for implementing resident protection measures. While the existing manual specifies the departments in charge, it lacks clarity on the specific individuals responsible, leading to ambiguity in roles and authority. The manual must explicitly designate personnel and clearly define their responsibilities.

Developing and distributing a standardized manual across different local governments is an effective strategy to ensure consistency in creating resident protection plans. By incorporating detailed local characteristics into a unified manual, specific tasks and responsible individuals can be clearly identified, minimizing confusion and establishing well-defined roles and responsibilities for all personnel involved.

Characteristics of radiological disaster

Radiological disasters exhibit several unique characteristics that necessitate specialized approaches in their management and response. Understanding these distinct characteristics is essential for developing a robust, adaptable, and comprehensive response system. Table 1 summarizes the key characteristics of radiological disasters [9].

This comprehensive understanding of the characteristics of radiological disasters allows for the development of effective response systems that not only focus on immediate containment and protection measures but also incorporate long-term strategies for recovery, communication, and international collaboration.

Definition of resilience engineering

Resilience engineering focuses on enhancing the ability of systems or organizations to anticipate, prepare for, respond to, and recover from unexpected disruptions. This approach is particularly valuable for bolstering radiological emergency preparedness and response [11, 12].

It involves developing flexible and efficient responses to manage disruptions *response*, continuously observing systems to detect early signs of trouble *monitoring*, analyzing past incidents to improve future preparedness and response *learning*, and identifying potential threats and vulnerabilities before they manifest ('anticipating') [13]. By implementing these prin-

Table 1. Characteristics of radiation disaster

Characteristics	Description
Long-lasting impact	The effects of radiological disasters can persist for decades or even centuries due to the long half-lives of radioactive materials, necessitating continuous recovery efforts.
Extensive contamination area	Radioactive materials can be dispersed over great distances by wind and precipitation, leading to widespread contamination of soil, water, and agricultural products.
Complex response and recovery	Effective management requires a co-ordinated approach addressing both immediate containment of radioactive sources and long-term community protection.
Need for international cooperation	Cross-border radiation spread necessitates cooperation among affected countries and international organizations to share information and resources effectively.
Severe health risks	Exposure to radiation can cause both acute effects (such as radiation sickness) and long-term consequences (including increased cancer risk and genetic mutations), necessitating long-term medical surveillance.
Socio-economic impact	Contamination can lead to displacement of communities, disruption of local economies, and long-term declines in agricultural and industrial activities.
Invisible danger	Radiation is not detectable by human senses, making it impossible to perceive without specialized equipment, which can delay recognition of danger and protective measures.
Radiological waste management	Radiological disasters produce substantial amounts of radioactive waste, requiring stringent protocols for safe handling, storage, and disposal to prevent further contamination.
Psychological and social effects	Fear and anxiety about radiation exposure can lead to public panic and unrest, highlighting the importance of transparent communication.

Table 2. Core principles of RE for disaster response

Core principles	Description
Response	To develop flexible and efficient strategies to handle disruptions; to create dynamic emergency plans adjustable in real time as situations change; to ensure all stakeholders are equipped to respond quickly and effectively during emergencies, such as radiological incidents
Monitoring	To continuously observe systems within resilience engineering; to implement advanced technologies and protocols; to detect early signs of problems; to enable timely intervention before situations escalate
Learning	To learn from past incidents; to enhance future preparedness and response; to examine previous emergencies and outcomes; to identify successful practices and areas for improvement; to develop stronger emergency protocols
Anticipating	To recognize potential threats and vulnerabilities; to implement proactive measures; to conduct comprehensive risk assessments; to engage in scenario planning; to carry out regular training exercises to ensure preparedness for various potential incidents

ciples, organizations can significantly enhance their capacity to effectively manage radiological disasters and minimize their impact on public safety. Table 2 summarizes the definitions of the four key concepts integrated in resilience engineering: response, monitoring, learning, and anticipating. Each of these concepts plays a critical role in enhancing the preparedness and effectiveness of systems in managing radiological disasters.

Design of survey question

In designing the survey questions, we analyzed the current radiological disaster response manuals, using them as a foundation for our assessment. This analysis considered both the principles of resilience engineering and the unique characteristics of radiological disasters. By integrating these factors, we aimed to develop survey questions that effectively capture the challenges and needs related to radiological disaster preparedness and response.

The survey questions were formulated to elicit insights from personnel involved in the implementation of disaster response measures, ensuring that they address relevant issues and gaps identified during the analysis. This approach facilitates the gathering of valuable feedback that can inform improvements to existing response protocols and enhance overall preparedness in the face of radiological disasters. Figure 2 shows the connection between the features of the radiation disaster and the RE perspective and leading to the derivation of survey questions.

RESULTS

Opinion collection for the improvement of the resident protection manual

To derive improvements for the resident protection manual by collecting opinions from the field, a survey was conducted using a structured questionnaire that targeted field personnel and relevant experts. Table 3 summarizes the affiliations and relevant NPP sites of the field personnel and experts who participated in the survey.

The survey on the resident protection manual included questions about the status and specific improvement plans for identified areas of enhancement. Designed to elicit open responses, the survey questions allowed participants to freely express their opinions. Conducted through face-to-face interviews, questionnaires were distributed to the respondents for them to fill out. To ensure anonymity, the organizations were labeled as A to E in the survey results. The respondents comprised public officers and employees from environmental monitoring agencies within the five local governments responsible for radioactive disaster prevention in areas with nuclear facilities.

Scenario development of resident protection (*Response*)

Recognizing the importance of a resident protection manual that considers weather conditions, geography, and population distribution underscores the difficulties in creating detailed accident response plans. These challenges mainly arise from personnel shortages and the complexities of developing scenarios. The survey respondents' answers are presented in tab. 4.

In summary, the survey highlighted that all agencies are making efforts to develop and enhance resident protection manuals based on available information. However, they are encountering challenges due to heavy workloads and limited human resources, which hinder their ability to conduct comprehensive regional analysis and develop/improve accident response scenarios. To address these issues, two potential solutions were proposed: allocating additional human resources to local governments to facilitate these tasks, or conducting an independent analysis of regional characteristics by central or specialized agencies and sharing the findings with local governments to support scenario development and improvement.

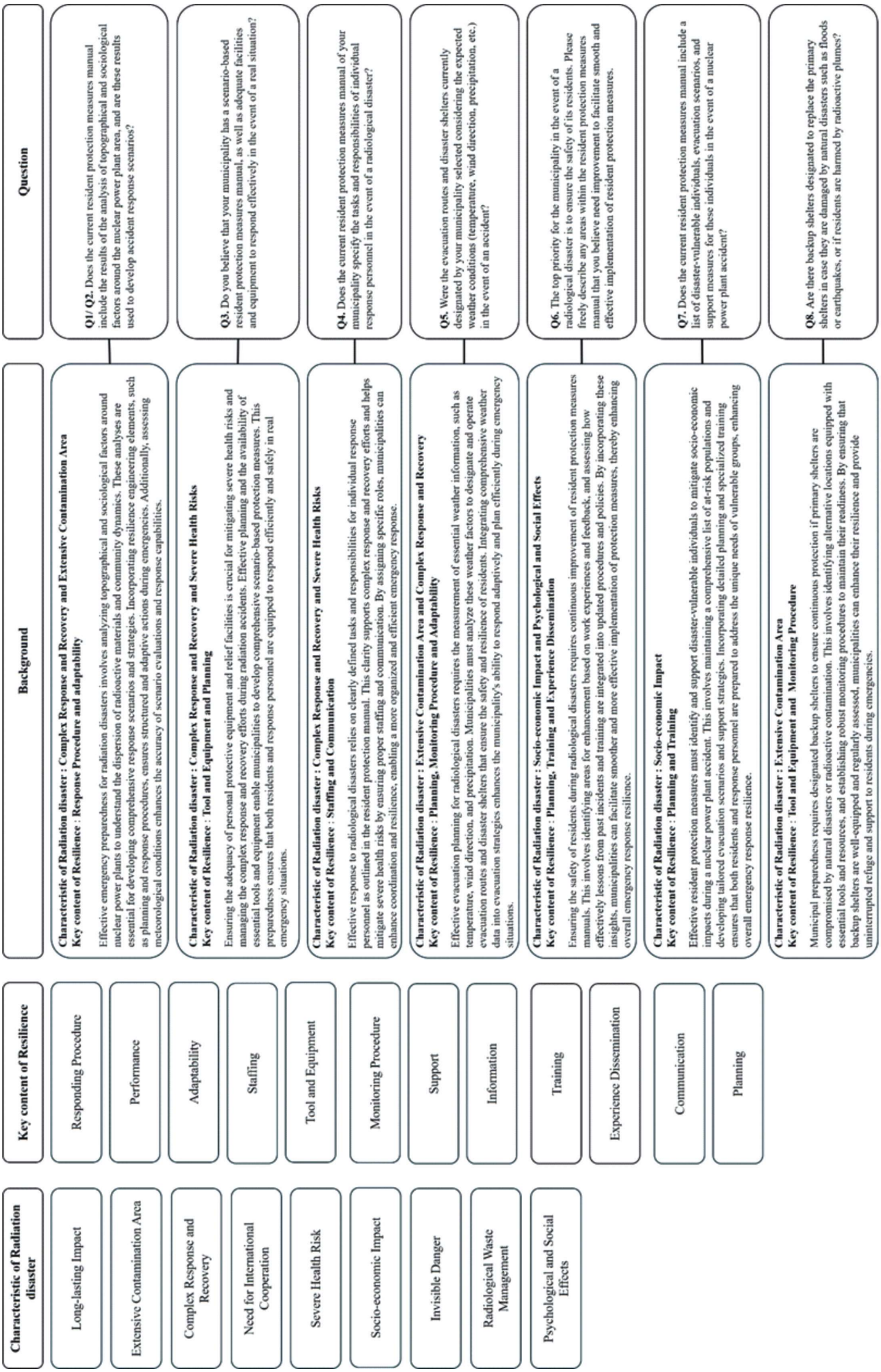

Figure 2. Relationship between components of resilience engineering and the survey questionnaire

Table 3. List of institutions to be surveyed for feedback

Classification	Organization	NPP site	Number of people
Monitoring committee	Wolsong Nuclear Facility Environment & Safety Monitoring Committee	Wolsong	5
	Yeong Gwang NPP Private Environment Supervisory Organization	Hanbit	5
Local government	Gyeongju-si	Wolsong	2
	Ulju-gun	Saewool	2
	Gijang-gun	Gori	1
		Total	15

Table 4. Opinions of respondents on the scenario development of resident protection

(Q1/Q2) Subject : Response – Responding Procedure / Adaptability	
Does the current resident protection measures manual include the results of the analysis of topographical and sociological factors around the nuclear power plant area, and are these results used to develop accident response scenarios?	
Agency A	The analysis results of the meteorological conditions and population distribution are reflected in the resident protection action manual. However, the responsibility for this task is assigned to a small number of personnel in charge of disaster prevention, and there is insufficient manpower to perform the task effectively.
Agency B	Our agency conducts comprehensive analysis that includes the evaluation of the distribution of social facilities, as well as the analysis of the terrain, population distribution, and road conditions. The results of this analysis are being used to develop a resident protection scenario.
Agency C	Our agency conducted a similar analysis to the other agency for the protection of residents. In addition to considering weather, geography, and population distribution, the analysis also included the assessment of surrounding traffic conditions based on the distance from the NPP, as well as the presence of industrial and medical facilities. The findings from this analysis were incorporated into the resident protection manual.
Agency D	The resident protection manual includes the results of meteorological and geographical analysis, but it lacks a comprehensive incorporation of population distribution analysis. The respondent also expressed challenges in developing accident response scenarios that encompass various potential situations, including those that may arise in actual accidents.

Shelter designation status (*Response/Anticipating/Monitoring*)

The agencies expressed confidence in their ability to effectively respond to disaster situations using the shelters managed by local governments, and each agency is currently working towards improving the functionality of these shelters to ensure more reliable responses in the future.

However, although local governments have requested a change in the system for improving shelters, there is a lack of clear position or direction from the central government or specialized organizations, resulting in delays in the improvement efforts. Overall, while progress is being made at the organizational level, the lack of coordination and support from higher-level authorities has been identified as a hindrance to the improvement of shelters. Alternatively, some agencies have taken the initiative to develop and implement systems, such as smart radioactive disaster prevention command and control, disaster management, and resident evacuation route systems.

In this context, the *smart radioactive disaster prevention command and control* is possible to integrate personal information such as migrants' residences and medical records. It also measures and records radiation exposure doses when entering aid stations, using them as reference until detailed measurement records are obtained. This system is advantageous for continuous individual record management in a disaster situation.

These systems are aimed at further enhancing the capabilities of the shelters. It is requested that local governments establish clear criteria for the designation of shelters, upgrade the equipment and systems in place to ensure the protection of residents during their stay at these shelters, and provide institutional support to ensure regular inspection and management of all designated shelters.

In addition to the opinions on improving the performance of evacuation facilities, opinions on the designation of shelters were gathered. One of the survey respondents, Agency A, did not consider weather conditions, such as wind direction, when selecting the current shelters and evacuation route. In contrast, Agency B and C considered weather conditions when designating evacuation routes and shelters. Additionally, they designated and operated backup shelters to address emergency situations. Table 5 summarizes the opinions on the designation of shelter.

(Answer 8) Considering weather conditions and having backup shelters can greatly enhance the effectiveness and safety of evacuation plans during a radioactive disaster. It is important for all agencies involved to prioritize these factors when selecting and operating shelters to effectively protect residents.

Establishment of a standardized manual (*Response/Learning/Anticipating*)

Except for Agency B, many investigative bodies expressed support for clearly defining responsibilities

Table 5. Opinions on shelter status

(Q3/Q5) Subject : Monitoring – Monitoring Procedure / Response – Tool and Equipment/Adaptability	
Do you believe that the respective local government currently has an adequate scenario-based resident protection measures manual and sufficient facilities and equipment to respond to actual situations?	
Agency B	Agency B has developed a preliminary plan for identifying aid stations based on 16 different wind directions. Additionally, they recognize the importance of implementing a comprehensive system for the ongoing inspection and management of shelters situated outside the jurisdiction of the local government where the NPP is located.
Agency C	Agency C conducts comprehensive data analysis, including temperature and wind direction analysis, to prepare for complex disasters, and incorporates this information into the operation of shelters. The agency has already pre-designated shelters based on regions and adjusts its response to the situation accordingly. However, the survey revealed that the shelter in the area where Agency C is located faces challenges in terms of capacity, as it cannot sufficiently accommodate the number of people requiring assistance during emergencies.

Table 6. Opinions on the establishment of standardized manual

(Q4/Q6) Subject : Response – Staffing / Learning – Experience Dissemination	
Does the current resident protection measures manual of the respective local government specify the tasks and responsibilities of individual response personnel in the event of a radiological disaster? Do you think it would be beneficial to designate individuals for specific roles?	
Agency B	Assigning tasks to individuals is not practical because of the frequent movement of personnel between departments. Therefore, a mission-based approach, in which missions, roles, and responsibilities are assigned to each department and team should be adopted.
Agency C	The detailed action procedures are currently being developed to supplement the existing manual system. These procedures aim to provide comprehensive and detailed descriptions of the assigned missions for agencies, departments, teams, and individuals.

and tasks not only for the responsible department but also for the individuals performing the actions in the current manual. Agencies comments on standardized manuals are summarized in tab. 6.

Scenario development of disaster-vulnerable population protection (*Anticipating*)

All surveyed agencies recognized the importance of preparing various support measures for the disaster-vulnerable population, however, only agency C was in the process of compiling a list of the disaster-vulnerable individuals. Additionally, they were seeking to develop scenarios and support plans specifically tailored to aid the disaster-vulnerable population.

(**Answer 7**) All agencies were actively working on developing more detailed support plans for vulnerable individuals residing in nursing facilities, such as hospitals, nursing homes, and nursing hospitals, excluding those living in private homes. A common approach among these agencies involved matching facilities of the same type in other regions on a one-to-one basis, while considering the number and type of nursing facilities in the area for evacuation purposes. Agency C was considering the distribution of thyroid protection medicine to vulnerable individuals prior to their relocation during the early stages of an accident. Additionally, regular on-site visits are to be conducted periodically to manage medication and transportation, and some respondents highlighted the need to clarify and specify the concept of vulnerability in the context of disasters to ensure that appropriate support is provided.

Proposals for improving the resident protection manual

This paper presents an improved version of the manual, informed by findings from resilience engineering and the survey process. During the feedback collection, several key areas for improvement were identified, including the need for better coordination of individual tasks, clearer delineation of roles across local, regional, and central governments, legal and institutional reforms for designating alternative shelters, enhancements to training methods, and support for staff during extended recovery periods. Additionally, the importance of providing fundamental information by analyzing accident risks and preparing for potential scenarios was highlighted. The revised manual, incorporating this critical feedback, is structured as illustrated in fig. 3. Improvements were achieved by adding or integrating essential elements into the existing framework, with a focus on addressing current system deficiencies. In the improved manual, feedback collected from the existing manual has been incorporated, distinguishing between the newly established sections and those that require further enhancement.

This improvement diagram outlines essential areas for enhancing the radiological disaster response manual. Baseline Analysis is crucial for establishing a clear understanding of current preparedness levels, so systematic methodologies for data collection should be included. Risk Factor Analysis enhances disaster preparedness by identifying and prioritizing potential hazards, necessitating structured assessments to develop specific response strategies. The Central & Local Support Plans require clear definitions and improved coordination to ensure effective execution during emergencies. Disaster Response Scenarios should provide diverse examples for practical application in the resident protection manual. Addressing the needs of vulnerable populations through targeted support measures and specialized training for personnel is essential. A robust Training Plan must be established with regular schedules and feedback mechanisms to continuously improve effectiveness. Finally, Reserve

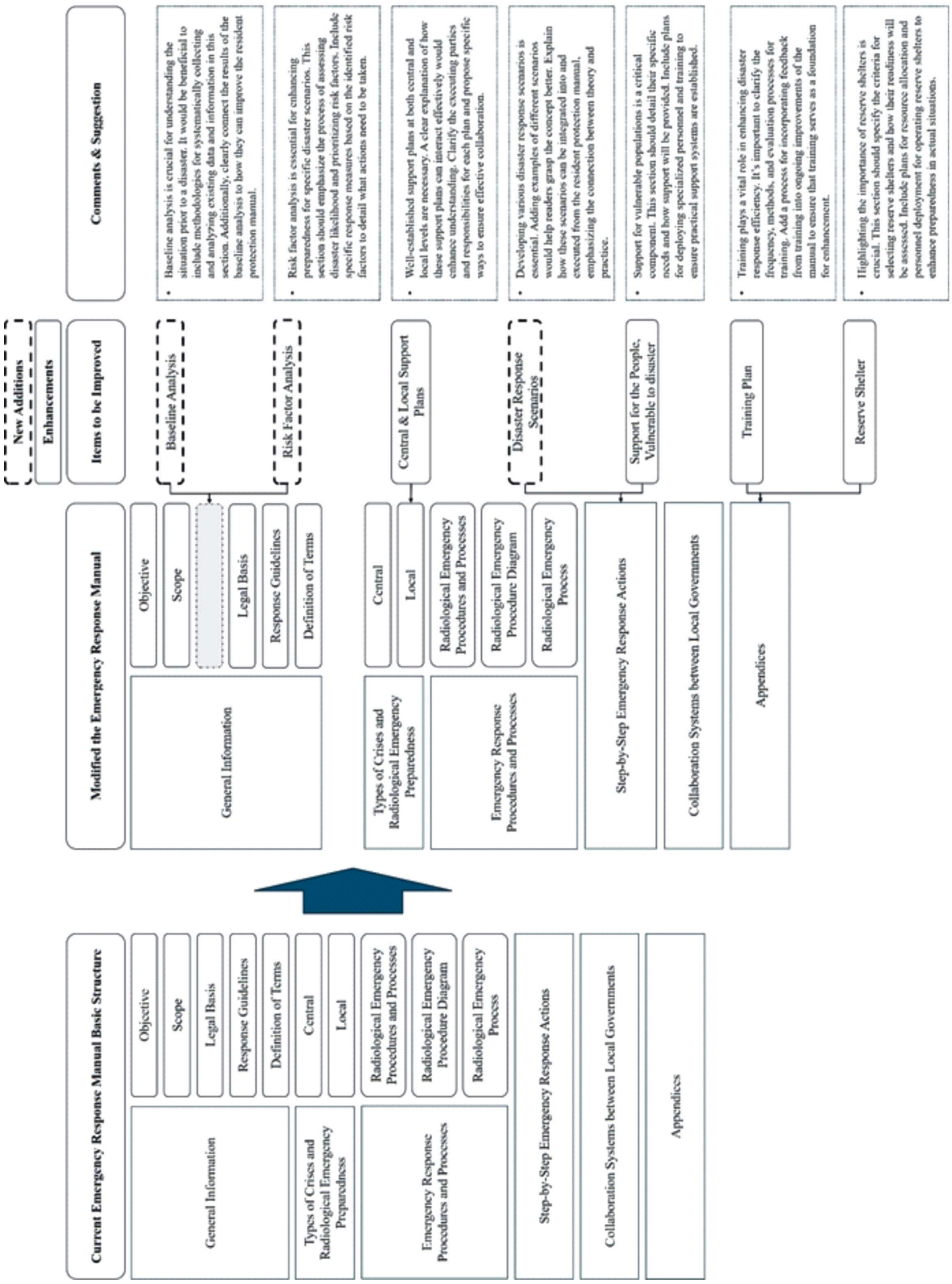

Figure 3. Framework for improving radiological disaster response manuals

Shelters should be designated with clear criteria and undergo regular readiness assessments to maintain protection during crises.

DISCUSSION

Our findings reveal that while local governments acknowledge the importance of developing detailed response scenarios for radiological disasters, a significant gap remains in the capacity to independently generate and implement these scenarios due to a shortage of specialized personnel. The survey results also highlight considerable disparities in the understanding of disaster prevention tasks and the application of resident protection manuals among different agencies. Such differences-correlated with respondents' roles and experience levels-indicate a pressing need for systematic training and enhanced inter-agency communication. Furthermore, the study underscores the necessity for robust institutional support, both in terms of human and material resources, to establish resilient and effective response measures for future radiological emergencies.

CONCULUSION

This study contributes to disaster management literature by empirically demonstrating the critical need for enhanced human resource allocation and institutional support to develop and implement effective radiological disaster response strategies near NPP. The results underscore the value of resilience engineering principles in identifying practical improvements and provide concrete recommendations for policy-makers to strengthen local response capabilities. These insights pave the way for future research and targeted interventions aimed at bolstering public safety and reducing the adverse impacts of radiological disaster.

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AUTHORS′ CONTRIBUTIONS

H. Y. Joo: investigation, visualization, writing – original draft, software, formal analysis. J. H. Moon supervision, writing – review and editing, conceptualization.

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ПОБОЉШАЊЕ ПРИРУЧНИКА ЗА РЕАГОВАЊЕ НА РАДИОЛОШКЕ КАТАСТРОФЕ У РЕПУБЛИЦИ КОРЕЈИ КРОЗ ИСТРАЖИВАЊЕ ЗАСНОВАНО НА ИНЖЕЊЕРСТВУ ОТПОРНОСТИ

У раду се процењују важећи приручници за реаговање у случају радиолошких катастрофа за заштиту становника у близини нуклеарних електрана у Републици Кореји, што је кључни аспект спремности за радиолошке ванредне ситуације. Истраживање идентификује стратегије за побољшање засноване на подацима прикупљеним од хитних служби у регионима у близини нуклеарне електране користећи анкетни упитник заснован на принципима инжењеринга отпорности. Кључне области у средишту пажње укључују анализу еколошких и друштвених фактора, стандардизацију, оптимизацију склоништа и развој сценарија за угрожене групе. Студија препоручује прерасподелу одговорности на нивоима власти, побољшање канала комуникације, одржавање стручности у приправности за ванредне ситуације и обезбеђивање одговарајућих финансијских и људских ресурса локалним самоуправама за ефикасну имплементацију ових побољшања.

Кључне речи: приручник за реаговање на радиолошке ванредне ситуације, радиолошка спремност за ванредне ситуације, испитивање, инжењеринг отпорности, нуклеарна електрана