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RELATIONSHIP BETWEEN SITE INFRASTRUCTURE AND THE EFFECTIVENESS OF ENVIRONMENTAL FIRE PROTECTION SYSTEMS IN SEI RENGAS PERMATA SUBDISTRICT, MEDAN CITY, INDONESIA

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ABSTRACT

High-density residential settlements are highly vulnerable to fire hazards due to inadequate supporting infrastructure, including limited road access, water supply, hydrants, and open spaces. Despite this, studies evaluating the effectiveness of fire protection systems in residential areas with relatively lower population density remain limited. This study aims to evaluate the condition of site infrastructure, analyze the effectiveness of the environmental fire protection system, and identify the relationship between site infrastructure and the effectiveness of the environmental fire protection system in Sei Rengas Permata Subdistrict, Medan Area District. A mixed-methods approach was employed, incorporating field observations, semi-structured interviews, documentation, and a scoring-based assessment using the aspects of availability, condition, and compliance with established standards. The findings indicate that Sei Rengas Permata Subdistrict achieved an average effectiveness score of 2.49, which falls within the effective category. Communication facilities received the highest score (3.00), while water supply sources recorded the lowest score (2.08). The analysis further reveals that building layout, neighborhood access roads, accessibility to fire stations, open spaces, water supply sources, yard hydrants, and communication facilities are interrelated in supporting the effectiveness of the environmental fire protection system. In contrast, the close spacing between buildings in several locations has the potential to accelerate fire spread. Therefore, improving the quality of the environmental fire protection system requires an integrated approach through the optimization of all site infrastructure components to enhance the resilience of residential areas against fire hazards.

KEYWORDS: Site Infrastructure; Environmental Fire Protection System; Effectiveness.

1. INTRODUCTION

In general, the highest fire risk occurs in densely populated residential areas, particularly in urban environments. Urban population density is primarily driven by rapid urbanization, which often results in unplanned land use and a reduction in open spaces [1] [2]. These open spaces are essential as evacuation areas and as buffers that help limit the spread of fire. Fire response is further hindered by

limited access to water supply and hydrants, narrow roads, traffic congestion, and inadequate firefighting equipment and building protection systems. In addition, insufficient fire safety training and public education reduce the preparedness of both local communities and emergency response personnel [3]

Therefore, planning for densely populated residential areas should adopt a comprehensive disaster risk reduction approach by integrating the improvement of road access, regulation of building materials, and provision of adequate firefighting facilities. Without such systematic measures, residential areas will remain highly vulnerable to fire hazards and their associated impacts. Effective urban planning is therefore essential, including the provision of clear evacuation routes, adequate access for fire engines, and green open spaces that function as buffers between buildings to effectively reduce fire risk [4].

Furthermore, the [5] states that urban fire protection management should not only focus on city-level planning but also on strengthening fire protection systems at the neighborhood level. Through the implementation of the Neighborhood Fire Resilience System and the Environmental Fire Protection System, each residential area is expected to possess the fundamental components necessary to support both fire prevention and emergency response. Within this framework, site infrastructure plays a crucial role, as it governs the arrangement and configuration of buildings to minimize the potential for fire spread while ensuring that the built environment has adequate structural preparedness to respond effectively to fire incidents.

Numerous studies have examined fire hazards in high-density residential settlements; however, most have focused primarily on fire risk mapping, identifying the underlying causes of fire incidents, or developing mitigation strategies.[6], for example, developed a fire risk assessment for informal settlements in Medan City by identifying key risk factors, including building materials, electrical installations, road width, and building density, and subsequently proposed resilience strategies through physical development, regulatory measures, and risk management approaches. Nevertheless, their study did not comprehensively evaluate site infrastructure as an integrated set of components that supports the effectiveness of the environmental fire protection system. Therefore, evaluating site infrastructure remains an important research priority, particularly in the context of high-density residential settlements in Indonesia.

One of the cities facing challenges related to limited land availability, increasing residential density, and a growing risk of fire incidents is Medan City. As the capital of North Sumatra Province and one of Indonesia's largest metropolitan cities, Medan has experienced rapid urban expansion, resulting in a continuous increase in demand for residential land while the availability of urban space has become increasingly constrained [7] [8]. These conditions have contributed to the development of densely built residential areas, thereby increasing their vulnerability to fire hazards. According to the 2024 Medan City Sectoral Statistics Compilation, Medan Area District has a population density of 21,505 inhabitants/km². Furthermore, based on Medan Area District in Figures 2025 [9], Sei Rengas Permata

Subdistrict has a population density of 15,667 inhabitants/km². Although its population density is relatively lower than that of several other subdistricts within Medan Area District, this area was selected as the study site to evaluate whether its existing site infrastructure is sufficient to support the effectiveness of the environmental fire protection system.

Based on the foregoing, this study aims to analyze the relationship between site infrastructure and the effectiveness of the environmental fire protection system in the high-density residential settlement of Sei Rengas Permata Subdistrict. The analysis was conducted by identifying the existing condition of each site infrastructure component, evaluating the effectiveness of the environmental fire protection system, and examining the relationship between these two aspects. The findings are expected to provide a better understanding of the role of each site infrastructure component in supporting the effectiveness of the environmental fire protection system and to serve as a basis for developing recommendations to enhance the fire resilience and preparedness of high-density residential settlements.

2. METHODOLOGY

2.1. Research Approach (Research Design)

This study employed a mixed-methods approach using a Sequential Explanatory design, integrating quantitative and qualitative methods to achieve a more comprehensive understanding of the relationship between site infrastructure and the effectiveness of the environmental fire protection system. According to [10], a mixed-methods approach enables the integration of measurable quantitative data with qualitative data that provide contextual explanations and deeper insights into the underlying causes of a phenomenon. In the quantitative phase, field observations and a scoring technique were conducted based on indicators developed through the synthesis of theoretical frameworks, technical standards, and regulations related to environmental fire protection systems. The subsequent qualitative phase involved semi-structured interviews with local residents, subdistrict officials, firefighters, and representatives of the Regional Disaster Management Agency (BPBD) to explain the quantitative findings and identify the factors influencing site conditions.

Based on its characteristics, this study is classified as descriptive-evaluative research. According to [11], descriptive research aims to systematically describe the characteristics of a phenomenon, whereas evaluative research assesses the extent to which an object complies with predetermined criteria or standards. Data were collected through field observations, semi-structured interviews, documentation, and a literature review. Quantitative data were analyzed using a scoring technique, while qualitative data were analyzed through data reduction, data display, and conclusion drawing following the interactive model proposed by [12]. The validity of the research was ensured through content validity of the research instruments, while the credibility of the qualitative findings was strengthened through methodological triangulation and source triangulation.

2.2. Research Site Selection Method

The research site was selected in Medan Area District, Medan City, using a purposive sampling technique, in which the study area was intentionally chosen based on characteristics that align with the research objectives. Medan Area District was selected because it is one of the urban districts in Medan City with a relatively high population density, characterized by organically developed residential settlements, limited land availability, and physical environmental conditions that may influence the effectiveness of the environmental fire protection system. In addition, the district has experienced a number of fire incidents, making it an appropriate location for evaluating site infrastructure as an essential component of fire risk mitigation.

This study was specifically conducted in Sei Rengas Permata Subdistrict. The selection of this subdistrict was based on the consideration that, although Medan Area District generally has a high population density, Sei Rengas Permata Subdistrict has a relatively lower population density than several other subdistricts within the district. According to Medan Area District in Figures 2025 [9], the subdistrict covers an area of 0.25 km² and has a population density of 15,667 inhabitants/km² (Figure 1).

The selection of this study area was motivated by an identified research gap. Most previous studies on environmental fire protection systems have focused on residential areas with high to very high population densities, as these areas are generally considered to face greater fire risk. In contrast, this study evaluates a residential area with a relatively lower population density within a densely populated district to determine whether this condition is accompanied by adequate site infrastructure capable of supporting the effectiveness of the environmental fire protection system. Accordingly, this study is expected to demonstrate that a relatively lower population density does not necessarily indicate a higher level of fire protection preparedness. Therefore, evaluating site infrastructure components remains essential as a basis for developing strategies to improve fire safety and resilience in residential areas.

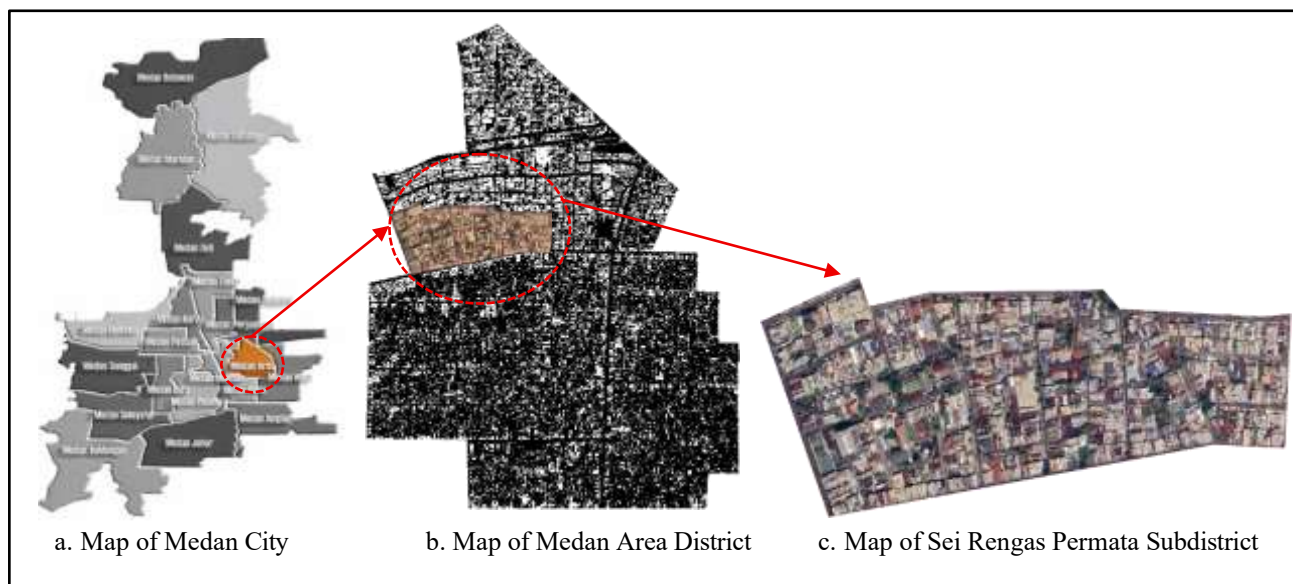


Figure 1: Research Area Location Map (a) Medan City Map; (b) Medan Area District Map; (c) Sei Rengas Permata Subdistrict Map

2.3. Population and Sampling Method

The study population comprised all residents living in Sei Rengas Permata Subdistrict, Medan Area District. In addition, the study involved key informants, including subdistrict officials, community leaders, and personnel from the Medan City Fire and Rescue Department, who possess relevant knowledge of the environmental fire protection system. Community respondents were selected using simple random sampling to obtain perceptions of the existing conditions of the study area, whereas key informants were selected through purposive sampling based on their experience, knowledge, and involvement in fire management and emergency response.

2.4. Variable Determination Method

The research variables were determined based on the study objectives and a review of relevant literature. The development of the variables, indicators, and parameters was guided by applicable regulations, technical standards, and previous studies related to environmental fire protection systems, including [13], [14], [5], and [15]. These references were used to ensure that the selected variables were appropriate for the characteristics of high-density residential settlements and aligned with the objectives of the study.

The study focused on site infrastructure as the primary research variable, which comprises eight subvariables: building layout and orientation, spacing between buildings, neighborhood access roads, water supply sources, yard hydrants, open spaces, accessibility to fire stations, and communication facilities. Each subvariable was further operationalized into specific indicators and parameters that served as the basis for identifying the existing condition of site infrastructure and evaluating the effectiveness of the environmental fire protection system in Sei Rengas Permata Subdistrict.

2.5. Data Collection Method

This study utilized both primary and secondary data. Primary data were collected through field observations, semi-structured interviews, and documentation, while secondary data were obtained from the literature, government regulations, technical standards, official government documents, and statistical data related to the environmental fire protection system. Field observations were conducted in Sei Rengas Permata Subdistrict to identify the existing condition of site infrastructure components based on the established research indicators. Semi-structured interviews were carried out with local residents, subdistrict officials, and personnel from the Medan City Fire and Rescue Department to obtain information regarding the condition of the environmental fire protection system, previous fire incidents, and challenges encountered in fire prevention and emergency response. Documentation was used to complement the observation and interview data through the collection of field photographs, maps, supporting documents, and records of fire incidents.

2.6. Data Analysis Method

Data analysis in this study employed both qualitative descriptive and quantitative descriptive approaches. The qualitative descriptive analysis was used to examine the existing condition of site infrastructure in the selected study area by comparing field observations with the applicable regulations and technical standards. Subsequently, the effectiveness of the environmental fire protection system was evaluated using a quantitative descriptive approach supported by a structured scoring technique based on the observed site conditions. The scoring technique was not intended as a statistical analysis; rather, it served as a systematic tool to facilitate the interpretation of qualitative data obtained from field observations, semi-structured interviews, and documentation [12] [10]. This approach enabled empirical findings to be organized consistently and transparently, thereby allowing a more structured comparison between existing site conditions and established fire protection standards.

Each parameter was assessed using three evaluation aspects: availability, condition, and compliance with technical standards. The availability aspect evaluated whether a fire protection component was present, the condition aspect assessed its physical and functional state, and the compliance aspect measured the extent to which the component met the applicable technical standards. For the availability assessment, three categories were applied: Not Available (NA), Available but Not Compliant (ANC), and Available and Compliant (AC). The condition assessment was classified into Poor (P), Fair (F), and Good (G). Compliance with technical standards was categorized as Non-Compliant (NC), Partially Compliant (PC), and Compliant (C) (Table 1). For data processing purposes, each category was assigned a numerical score ranging from 1 to 3, with higher scores representing better conditions. These scores were used solely as an interpretive framework for organizing and evaluating qualitative findings rather than as the basis for inferential statistical analysis [16].

Table 1: Scoring technique

A. Availability Scoring Criteria		
Category	Code	Score
Not Available	NA	1
Available but Not Compliant	ANC	2
Available and Compliant	AC	3
B. Condition Scoring Criteria		
Poor	P	1
Fair	F	2
Good	G	3
C. Tabel Skoring Kesesuaian terhadap Standar		
Non-Compliant	NC	1
Partially Compliant	PC	2
Compliant	C	3

Following the scoring process, the score for each parameter was calculated by averaging the scores of the three assessment aspects: availability, condition, and compliance with technical standards. The parameter score was calculated using the following equation:

$$\text{Parameter Score} = \frac{\text{Availability Score} + \text{Condition Score} + \text{Compliance Score}}{3}$$

Subsequently, the scores of all parameters within each indicator were summed and averaged to obtain the indicator score. The scores of all indicators within each subvariable were then aggregated and averaged to determine the final subvariable score. Accordingly, the subvariable score represents the overall condition of each assessed aspect based on the predetermined indicators and parameters.

To facilitate the interpretation of the assessment results, the average scores were classified into three effectiveness categories using the class interval method. The class interval was determined based on the minimum and maximum scores adopted in this study, ranging from 1 to 3 [17]. The class interval was calculated as follows:

$$\text{Class Interval} = \frac{\text{Maximum Score} - \text{Minimum Score}}{3} = \frac{3 - 1}{3} = 0,67$$

Based on this calculation, the effectiveness categories are presented in Table 2.

Table 2: Effectiveness categories of the environmental fire protection system

Average Score	Effectiveness Category
2,35 – 3,00	Effective
1,68 – 2,34	Moderately Effective
1,00 – 1,67	Ineffective

To identify the relationship between site infrastructure and the effectiveness of the environmental fire protection system, a descriptive-evaluative analysis was conducted by interpreting the findings obtained from field observations, semi-structured interviews, documentation, and the assessment scores for each research component. The analysis involved comparing the existing conditions with the applicable technical standards to explain the relationship between site infrastructure and the effectiveness of the environmental fire protection system in Sei Rengas Permata Subdistrict.

3. RESULT AND DISCUSSION

3.1. Site Infrastructure Conditions in Sei Rengas Permata Subdistrict

The analysis of site infrastructure conditions was conducted to evaluate the extent to which the physical characteristics of the study area support the environmental fire protection system. This analysis examined several key components of site infrastructure, including building layout and orientation, spacing between buildings, neighborhood access roads, water supply sources, yard

hydrants, open spaces, accessibility to fire stations, and communication facilities. These components were assessed to determine their contribution to the overall effectiveness of the environmental fire protection system in the study area.

3.1.1. Building Layout and Orientation

Building layout and orientation constitute one of the key site infrastructure components evaluated to describe the physical characteristics of the residential area. In this study, the analysis was conducted based on three components: building layout pattern, building opening orientation, and building arrangement in relation to the road network. These components were used to identify the characteristics of building configuration and to examine the relationship between buildings and the road network in Sei Rengas Permata Subdistrict.

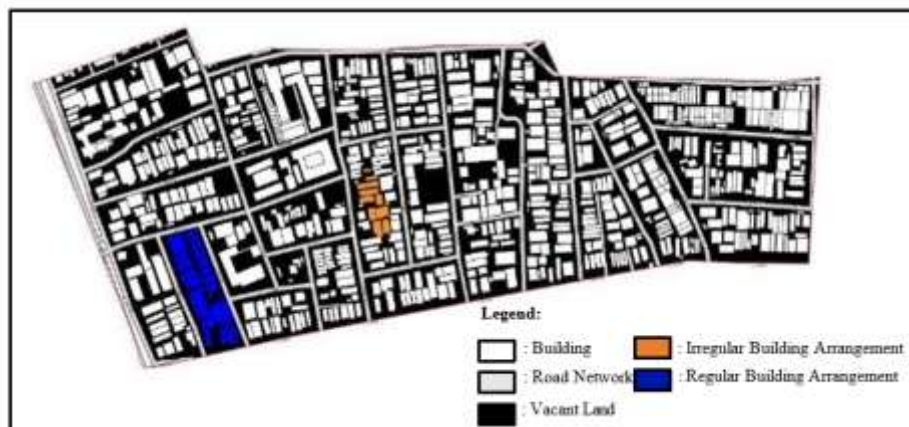


Figure 2: Building Arrangement Pattern Between Buildings

Based on the field observations, most buildings in Sei Rengas Permata Subdistrict are attached to one another with little or no separation within individual residential blocks, resulting in relatively low building spacing at the micro scale. Nevertheless, the settlement is organized into a grid-like block pattern separated by neighborhood access roads, providing physical separation between adjacent blocks. This indicates that the spatial separation of buildings in the study area is influenced more by the presence of the road network than by the spacing between individual buildings within each residential block (Figure 2).

On the other hand, the overall building layout generally follows the neighborhood road network, creating a relatively orderly settlement pattern. Most buildings are aligned parallel to the roads and form clearly defined residential blocks. Although several buildings exhibit non-uniform orientations due to the area's gradual and incremental development, the overall building layout in Sei Rengas Permata Subdistrict can be considered well organized, as it remains largely structured around the road network, which serves as the primary organizing element of the settlement (Figure 2).



Figure 3: Building Opening Orientation

Furthermore, the building openings are generally oriented toward the neighborhood roads or alleys, which serve as the primary access routes to the buildings. This is reflected in the predominance of doors and windows facing the circulation network, indicating that residents' daily activities are concentrated along the neighborhood access roads. In addition, the spacing between building openings is generally adequate, and most openings do not directly face one another. Overall, the orientation of building openings in Sei Rengas Permata Subdistrict follows the neighborhood road network, while variations in the configuration of openings are influenced by the building layout characteristics of each residential block (Figure 3).

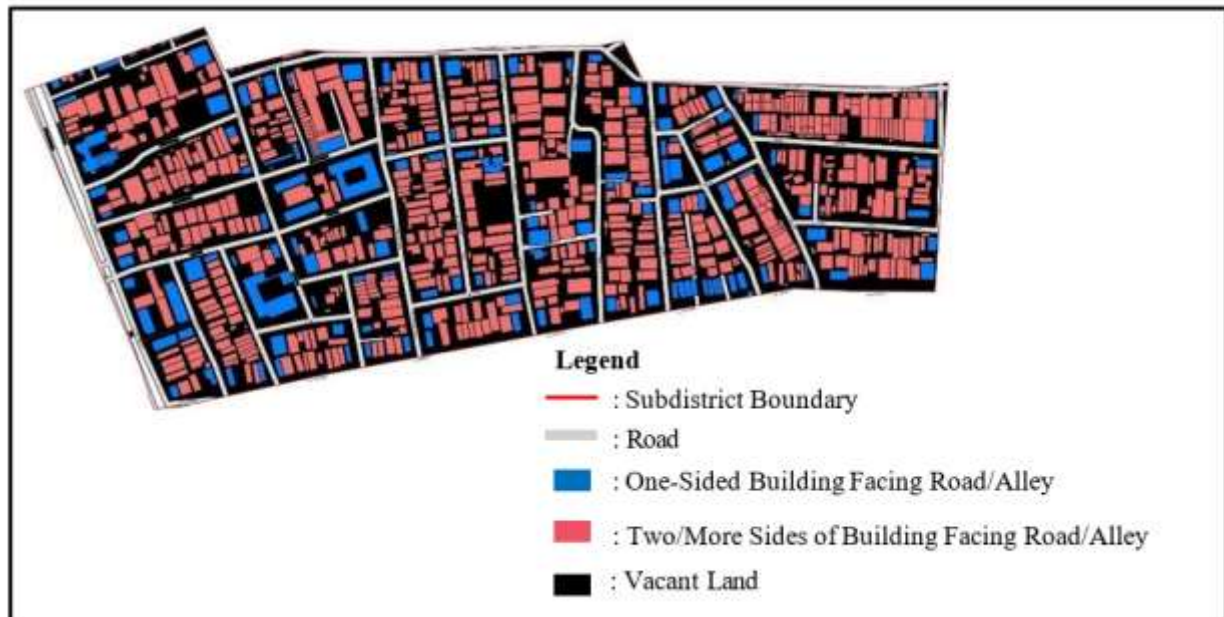


Figure 4: Building Orientation Toward Roads

Meanwhile, the arrangement of buildings in relation to the road network generally shows that one side of the building directly faces the neighborhood road or alley, while the other sides are adjacent to surrounding buildings. This condition creates rows of buildings that extend along the road network, resulting in a more structured settlement pattern. In several locations, buildings were also found at road intersections or with more than one side directly facing the road; however, such cases were relatively limited. Overall, the relationship between building arrangement and the road network indicates that roads serve as the primary elements shaping the settlement structure in Sei Rengas Permata Subdistrict (Figure 4).

3.1.2. Building Spacing

Building spacing is one of the site infrastructure components evaluated to describe the level of physical separation between buildings within the residential area. In this study, the analysis was conducted based on two components: the width of the distance between buildings and the presence of separation elements between buildings. These components were used to identify the characteristics of inter-building spaces and the types of physical separation existing in Sei Rengas Permata Subdistrict.



Figure 5: Building Spacing Width

The building spacing in Sei Rengas Permata Subdistrict remains varied. In most residential blocks, buildings are positioned relatively close to one another, resulting in limited spaces between adjacent buildings. This condition is particularly evident in rows of houses that have developed linearly within residential blocks. Meanwhile, several locations still have buildings with wider separation distances, particularly along areas adjacent to neighborhood access roads or open spaces. Overall, the building spacing in Sei Rengas Permata Subdistrict is not evenly distributed and remains dominated by buildings with relatively narrow separation distances within residential blocks (Figure 5).



Figure 6: Separation Elements (a) Drainage; (b) Narrow Gap; (c) Narrow Alloy; (d) Wide Gap

Furthermore, the building separation elements in Sei Rengas Permata Subdistrict consist of neighborhood access roads, drainage systems, pathways between buildings, and open gaps distributed across several parts of the area. The presence of these elements indicates physical separation between building blocks and groups of buildings, although their distribution is not evenly spread throughout the settlement. In some locations, separation elements are clearly visible, while in other areas buildings have developed with limited or no significant physical separation. Overall, the separation elements found in Sei Rengas Permata Subdistrict demonstrate variations in form and function; however, they have not yet become dominant features that shape the overall structure of the residential area (Figure 6).

3.1.3. Neighborhood Access Road

Neighborhood access roads are one of the key site infrastructure components that function as the primary access routes to residential areas. In this study, the condition of neighborhood access roads was analyzed based on four components: road width, road surface condition, maneuvering space, and road obstructions. These components were used to describe the physical characteristics of the road network in Sei Rengas Permata Subdistrict.



Figure 7: Road Width

The neighborhood access roads in Sei Rengas Permata Subdistrict are predominantly characterized by road widths ranging from approximately 3.5–6 meters. These widths are generally found on the main

neighborhood roads connecting residential blocks, while several inner-area roads have more limited dimensions. Visually, the road network provides relatively good connectivity between different parts of the settlement and reaches most residential blocks. This condition indicates that the width of neighborhood access roads in Sei Rengas Permata Subdistrict varies across the area; however, it is still predominantly composed of roads with wider dimensions compared to typical neighborhood access roads (Figure 7).

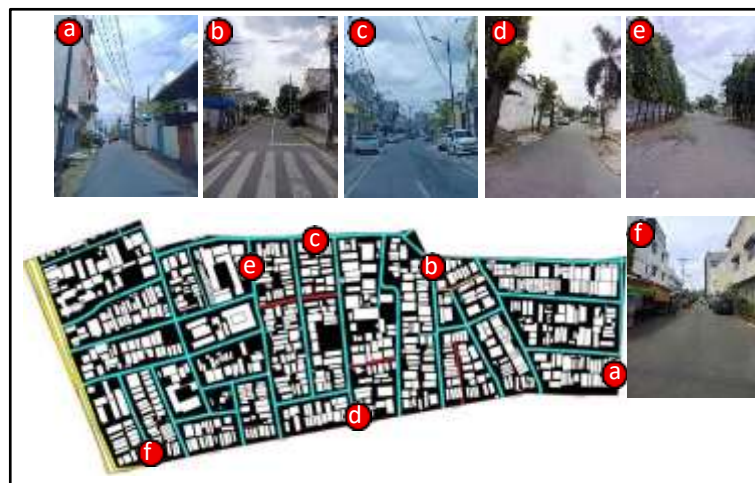


Figure 8: Road Surface Condition

In addition to road width, road surface condition is another important aspect that needs to be considered. The neighborhood access roads in Sei Rengas Permata Subdistrict are predominantly paved with asphalt and are generally in good condition. Most road sections have relatively flat and even surfaces, with no significant damage identified, such as potholes or surface deterioration. This condition is observed across the main neighborhood roads as well as several internal roads within the residential area. Overall, the road surface condition in Sei Rengas Permata Subdistrict demonstrates good physical quality and is supported by the use of adequate pavement materials (Figure 8).



Figure 9: Maneuver Area

Furthermore, the road network maneuverability in Sei Rengas Permata Subdistrict generally forms circulation routes that surround most residential blocks. This condition is reflected in the connectivity between road sections, which allows vehicle movement from more than one direction in several parts of the area. Nevertheless, some residential blocks are still located along dead-end roads or have limited circulation routes, resulting in uneven maneuverability throughout the settlement. Overall, the road network in Sei Rengas Permata Subdistrict has established a relatively clear circulation pattern and is capable of connecting most parts of the residential area (Figure 9).

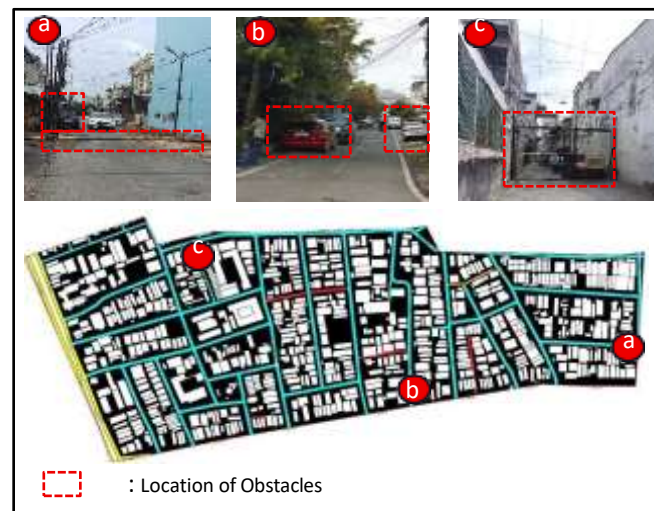


Figure 10: Road Obstacles

Meanwhile, regarding road obstructions, several road sections in Sei Rengas Permata Subdistrict still experience various obstacles that occupy parts of the road space. These obstructions include vehicles parked along the roadway, utility poles, roadside stalls or activities, and other physical elements that reduce the effective road width at certain points. Although these conditions are not present throughout the entire road network, they remain visible in several parts of the residential area. Overall, the neighborhood access roads in Sei Rengas Permata Subdistrict remain accessible; however, localized obstructions still affect the physical condition and effective capacity of the road space (Figure 10).

3.1.4. Water Sources

Water supply sources are one of the key site infrastructure components that function as water providers for fire suppression efforts. In this study, the condition of water supply sources was analyzed based on four components: water source origin, water source coverage, water availability capacity, and water source management. These parameters were used to describe the characteristics of available water supply sources in Sei Rengas Permata Subdistrict.

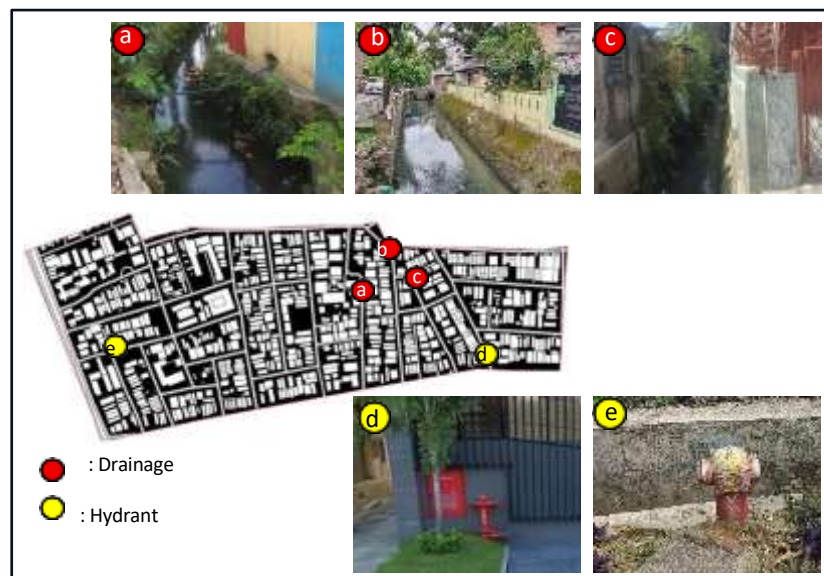


Figure 11: Water sources

The observation results indicate that water supply sources in Sei Rengas Permata Subdistrict are predominantly derived from artificial water sources, including the municipal water supply network (PDAM), drainage systems, and hydrants distributed across several locations. Meanwhile, natural water sources such as rivers, lakes, or ponds were not identified within the study area. The distribution of artificial water sources also shows different characteristics, where the PDAM network is available throughout most of the area, while hydrants are only found at specific and limited locations. Overall, this condition indicates that the availability of water supply sources in Sei Rengas Permata Subdistrict relies more heavily on artificial water infrastructure rather than natural water sources (Figure 11).

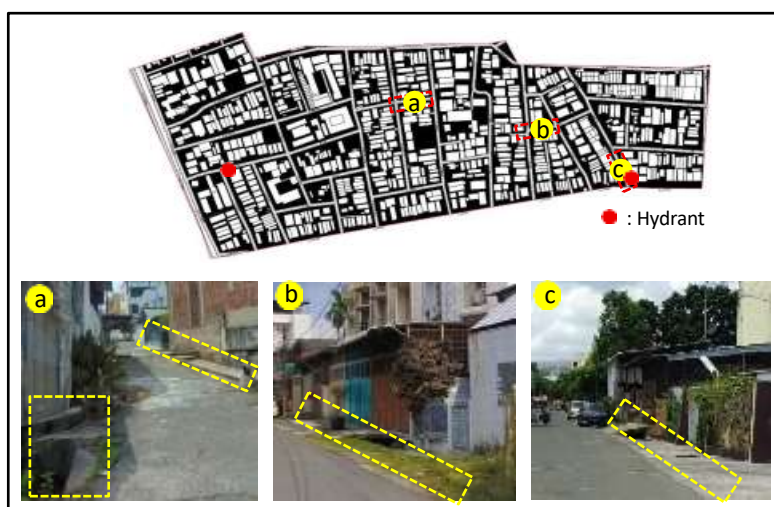


Figure 12: Drainage segments are covered

Furthermore, the water source coverage in this subdistrict is not evenly distributed throughout the area. The municipal water supply network (PDAM) is relatively accessible because it follows the distribution pattern of residential areas, whereas hydrants and drainage channels can only be accessed at specific locations. This condition results in varying levels of water source accessibility between different parts of the settlement, particularly in residential blocks located farther from available water supply points. Overall, the coverage of water supply sources in Sei Rengas Permata Subdistrict shows spatial variation, indicating that not all areas have the same level of accessibility to available water sources (Figure 12).

Similarly, the water supply capacity remains suboptimal. Available water sources, such as the PDAM network, are generally sufficient to support daily domestic needs; however, they are not specifically designed as water supplies for fire emergency situations. In addition, the water discharge of drainage channels within the area fluctuates depending on weather conditions, while the limited availability of hydrants results in uneven water supply capacity across the settlement. Overall, the capacity of water supply sources in Sei Rengas Permata Subdistrict has not fully met the requirements to support fire suppression activities.

Furthermore, there is currently no specific water source management system established to support the environmental fire protection system. Based on field observations, no facilities or management mechanisms were identified that designate water sources as part of fire preparedness efforts, such as routine maintenance, identification of water source locations, or regulation of their utilization during emergency conditions. Existing water sources are generally still used for their primary function, namely supporting daily community needs. Overall, this condition indicates that water source management in the study area remains general in nature and has not yet been integrated with the requirements of the environmental fire protection system.

3.1.5. Yard Hydrants

Yard hydrants are one of the key site infrastructure components that function as water supply facilities for fire suppression activities. In this study, the condition of yard hydrants was analyzed based on three components: hydrant reliability, hydrant accessibility, and hydrant service coverage. These parameters were used to describe the characteristics of hydrant availability in Sei Rengas Permata Subdistrict.

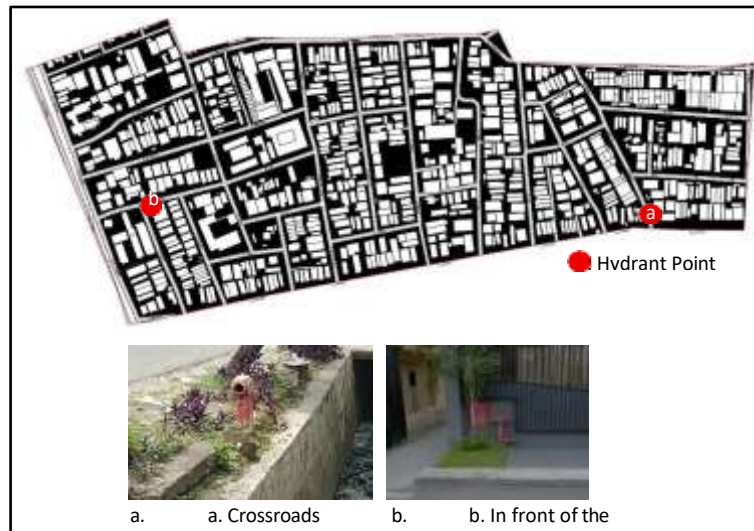


Figure 13: Hydrant reliability

Yard hydrants in Sei Rengas Permata Subdistrict are available at several locations within the study area; however, their quantity remains limited. Based on field observations, the physical condition of hydrants varies, with some hydrants still appearing to be in good condition, while others show signs of inadequate maintenance. In addition, not all hydrants have clear information regarding their operational condition or functional status. Overall, the reliability of yard hydrants in Sei Rengas Permata Subdistrict remains uneven due to limitations in quantity, physical condition, and the lack of optimal maintenance practices (Figure 13).

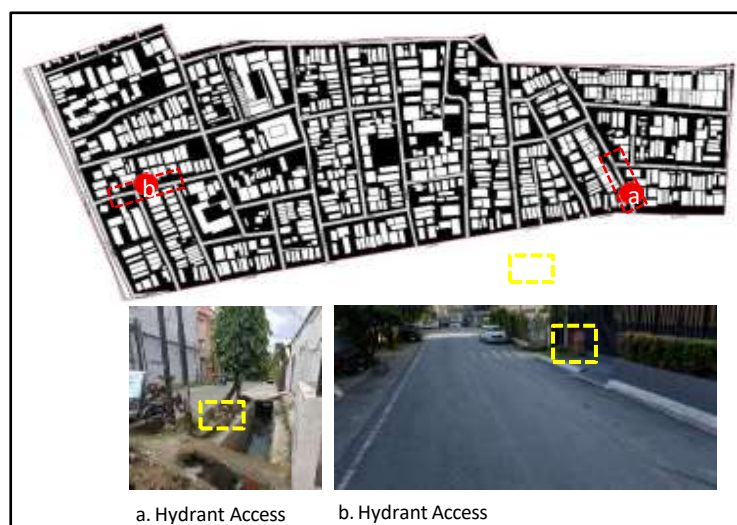


Figure 14: Hydrant accessibility

In addition to the physical condition of the hydrants, the location and accessibility of hydrants were also assessed in this study. Yard hydrants in Sei Rengas Permata Subdistrict are generally located along neighborhood access roads with relatively adequate widths, allowing them to be easily identified and accessed from the road network. Most hydrants are positioned in open areas without obstruction from permanent structures; however, their distribution remains limited to only several locations within the study area. As a result, not all parts of the settlement have equal access to the available hydrants. Overall, the accessibility of yard hydrants in Sei Rengas Permata Subdistrict is considered good at the locations where hydrants are available, although their distribution has not yet been evenly spread throughout the study area (Figure 14).

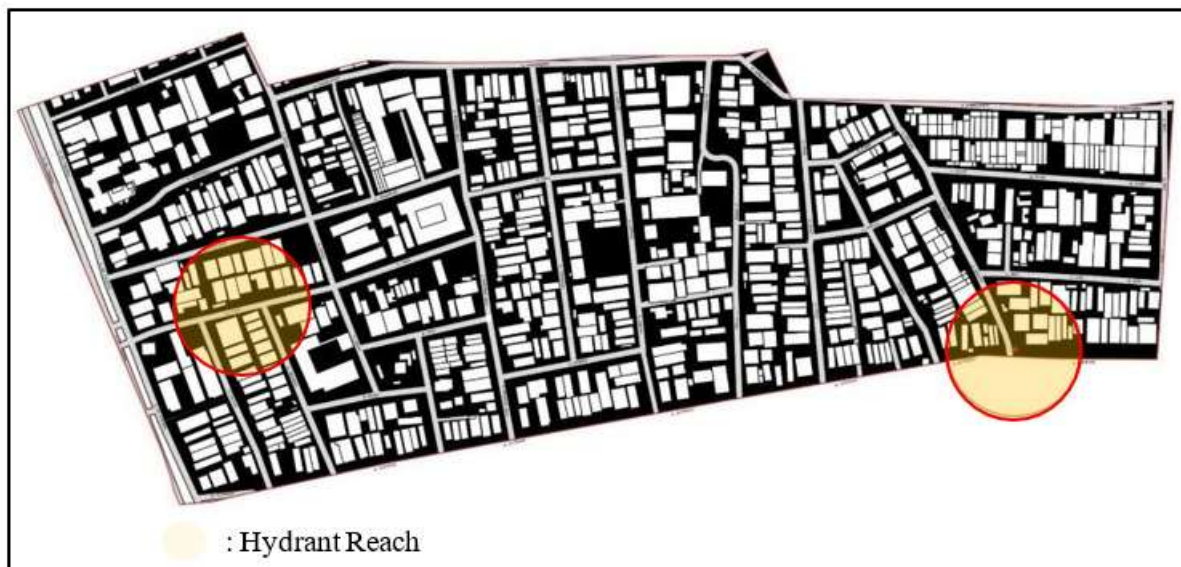


Figure 15: Hydrant service coverage

The limited distribution of hydrants also affects their service coverage. Based on field observations, the hydrant service coverage has not yet reached the entire residential area, resulting in several blocks remaining outside the effective service radius. This condition is reflected in the concentration of hydrants at only specific locations, while other parts of the settlement still lack adequate service coverage. Overall, the hydrant service coverage in Sei Rengas Permata Subdistrict is not evenly distributed, indicating that its effectiveness remains limited to the areas surrounding the available hydrant locations (Figure 15).

3.1.6. Open Space

Open space is one of the key site infrastructure components evaluated to describe the availability of open areas within the residential environment. In this study, the condition of open spaces was analyzed based on three components: types of open spaces, functions of open spaces, and dimensions of open spaces. These components were used to identify the characteristics of open spaces available in Sei Rengas Permata Subdistrict.



Figure 16: Types of open spaces

Sei Rengas Permata Subdistrict has several types of open spaces, including school yards, church courtyards as non-green open spaces, and small parks located around road intersections. These open spaces are distributed across several parts of the area; however, their quantity and size remain relatively limited, and no large-scale open spaces have been identified as dominant features within the residential area (Figure 16).

The presence of these open spaces provides different functions depending on the characteristics of each location. School yards and church courtyards have the potential to serve as initial evacuation areas or temporary parking spaces for fire trucks, while parks and other open spaces may function as separation zones between buildings. Nevertheless, these functions remain potential uses and are highly dependent on the actual conditions and requirements during emergency situations.

In addition to their types and functions, the size of open spaces was also assessed in this study. Most open spaces have relatively limited dimensions, resulting in insufficient capacity to accommodate multiple emergency response activities simultaneously. Overall, open spaces in Sei Rengas Permata Subdistrict are available in several forms; however, they are still predominantly characterized by small-scale open spaces with functions limited to specific locations.

3.1.7. Fire Station Accessibility

Accessibility to fire stations is one of the key site infrastructure components that represents the coverage and reach of fire and rescue services within residential areas. In this study, accessibility

conditions were analyzed based on four parameters: service coverage, response time, service radius, and the feasibility of access routes to the study area. These parameters were used to describe the characteristics of fire service accessibility in Sei Rengas Permata Subdistrict.

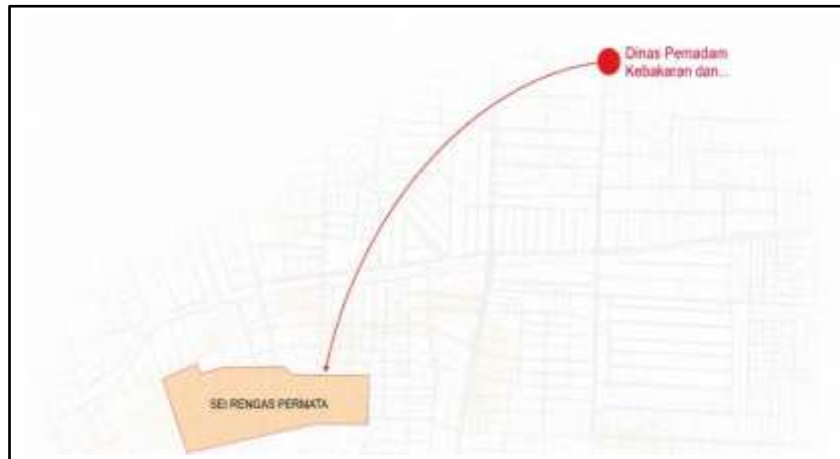


Figure 17: Service coverage

Based on the mapping results and interviews, it was identified that Sei Rengas Permata Subdistrict remains within the service coverage area of the nearest Fire and Rescue Unit (UPT) located in Medan Area District. The fire station serves three subdistricts within Medan Area District, including the study area. Therefore, the research location is still included within the operational area of the fire station, allowing fire and rescue services to reach the study area according to the established service coverage boundaries (Figure 17).

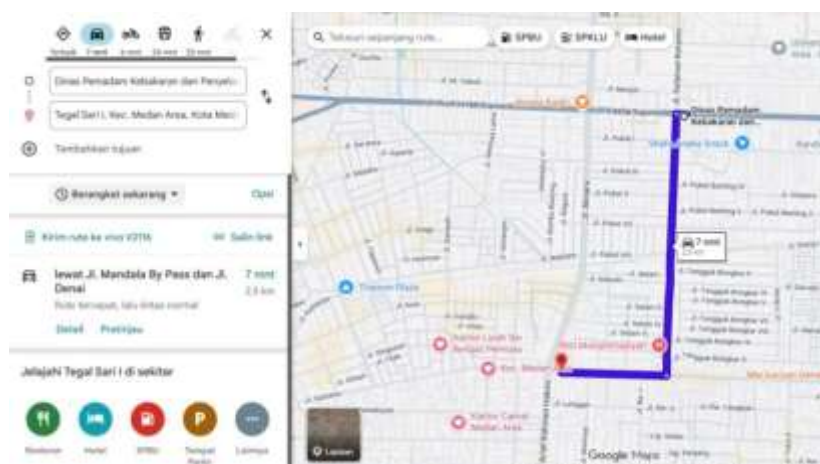


Figure 18: Response time

With this service coverage, the capability of the fire station is also determined by the time required to reach the incident location. The response time to Sei Rengas Permata Subdistrict is approximately 10–

11 minutes, based on the primary route connecting the fire station and the study area. Field observations indicate that the road network conditions and the location of the fire station allow personnel to reach the area within a relatively short period. Therefore, the response time meets the requirement of an emergency response duration of less than 15 minutes (Figure 18).

Although the response time to the study area meets the required standard, the location of the settlement in relation to the fire station's service radius also needs to be evaluated. Based on the spatial mapping results, Sei Rengas Permata Subdistrict remains within the operational coverage area of the fire station, with a distance of approximately 3.2–3.4 km. However, when compared with the ideal service radius of 2.5 km, the study area is still beyond the recommended coverage limit. This condition indicates that, operationally, the area can still be reached by fire and rescue services, although its distance has not yet fully complied with the ideal service radius requirement.



Figure 19: Access adequacy

In addition to service coverage, response time, and service radius, the accessibility conditions toward the study area were also assessed in this research. The route to Sei Rengas Permata Subdistrict is predominantly characterized by commercial, service, and residential areas with relatively low to moderate traffic activity. The main roads connecting the fire station to the study area are generally in good condition and accessible for fire vehicles, while access to the inner parts of the settlement is supported by interconnected neighborhood access roads (Figure 19).

Overall, the accessibility of the Fire and Rescue Station to Sei Rengas Permata Subdistrict demonstrates relatively good conditions, indicated by the area remaining within the operational service

coverage, response time meeting the required standard, and adequate accessibility to the study location, although the ideal service radius has not yet been fully achieved.

3.1.8. Communication Facilities

Communication facilities are one of the key site infrastructure components that play an important role in delivering information during fire emergencies. In this study, the condition of communication facilities was analyzed based on four components: types of communication media, reporting accessibility, reporting speed, and compliance with reporting procedures. These components were used to describe the characteristics of the communication system utilized by the community in Sei Rengas Permata Subdistrict.

Communication facilities in Sei Rengas Permata Subdistrict are predominantly supported by the use of mobile phones as the primary medium for information delivery. The availability of communication networks covering the residential area enables residents to communicate easily, both with other community members and relevant authorities. In addition to mobile phone communication, direct communication between residents remains an initial method of information exchange during emergency situations.

The availability of these communication facilities provides convenience for residents in reporting fire incidents. Based on field observations and interviews, residents are able to submit reports through telephone services or local community representatives without significant obstacles. This ease of communication is supported by public understanding of the reporting mechanism, allowing information delivery to follow the established procedures.

In addition to accessibility, residents also demonstrate an understanding of the fire reporting process, either through local community representatives or directly to the Fire and Rescue Department. A clear reporting flow enables information to be transmitted to the relevant authorities in a structured manner, thereby facilitating coordination among stakeholders involved in fire response activities.

This condition also contributes to the speed of information delivery during fire incidents. Interview results indicate that residents understand the appropriate actions to take when a fire occurs, allowing reports to be submitted promptly to the relevant agencies. Therefore, the communication process, from initial reporting to emergency response coordination, can be carried out efficiently.

Overall, the condition of communication facilities in Sei Rengas Permata Subdistrict indicates that the community is supported by adequate communication media, easy reporting access, an understanding of reporting procedures, and rapid information transmission, enabling effective communication during fire emergency response activities.

3.2. Effectiveness of the Environmental Fire Protection System Based on Site Infrastructure Conditions in Sei Rengas Permata Subdistrict

Following the identification of the existing site infrastructure conditions, the next stage involved evaluating the effectiveness level of each component in supporting the environmental fire protection system in Sei Rengas Permata Subdistrict. The evaluation was conducted using a scoring method based on three assessment aspects: availability, condition, and compliance with technical

standards. The assessment was developed based on field observations, interviews with local residents and relevant institutions, as well as documentation, which were subsequently compared with applicable technical requirements.

The assessment results indicate that the effectiveness level of each site infrastructure component varies. These variations reflect differences in physical conditions and infrastructure availability among the assessed components, resulting in different levels of effectiveness in supporting the environmental fire protection system. Therefore, not all components demonstrate the same level of contribution to improving fire protection performance within the residential area (Table 3).

Table 3: Effectiveness assessment in Sei Rengas Permata subdistrict

Sub-variable	Indicator	Parameter	Availability			Condition			Standard Compliance			Total Score	Average Score
			NA (1)	ANC (2)	AC (3)	P (1)	F (2)	G (3)	NC (1)	PC (2)	C (3)		
Building Layout and Orientation	Building Arrangement Pattern	Building Separation		2			2			2		6	2
		Regular Arrangement			3			3			3	9	3
	Indicator Score												2.5
	Building Opening Orientation	Position of Openings Relative to Adjacent Buildings			3			3			3	9	3
	Indicator Score												3
	Building Arrangement Relative to Roads	Number of Building Sides Facing Roads			3			3		2		8	2.67
	Indicator Score												2.67
	Total Sub-Variable Score												2.72
Building Spacing	Building Separation Distance	Safe Distance: 3 m (1–8 m height); >3–6 m (>8–14 m); >6–8 m (>14–40 m); >8 m (>40 m)		2			2			2		6	2
	Indicator Score												2
	Separation Elements	Firewalls / Open Spaces		2			2			2		6	2
	Indicator Score												2
	Total Sub-Variable Score												2
Neighborhood Roads	Road Width	3,5-6 meter			3			3			3	9	3
	Indicator Score												3
	Road Surface Condition	Paved with Durable Materials			3			3			3	9	3
		Relatively Flat Surface (Maximum Slope 1:8.3)			3			3			3	9	3

Water Sources	Indicator Score												3
	Vehicle Maneuverability	Fire Vehicle Circulation Around Buildings			3			3			3	9	3
	Indicator Score												3
	Road Obstacles	Fixed and Movable Obstructions		2			2			2		7	2.33
	Indicator Score												2.33
	Total Sub-Variable Score												2.83
	Availability of Water Sources	Natural and/or Artificial Sources			3		2			2		7	2.33
	Indicator Score												2.33
	Accessibility of Water Sources	Easily Accessible		2			2			2		6	2
	Indicator Score												2
Hidran halaman	Water Supply Capacity	Adequate Supply		2			2			2		6	2
	Indicator Score												2
	Water Source Management	Storage, Conservation, or Recycling	1			1				1		3	1
	Indicator Score												1
	Total Sub-Variable Score												1.83
	Hydrant System (Yard Hydrant)	Hydrant Reliability		2			2			2		6	2
	Indicator Score												2
	Hydrant Accessibility	Ease of access			3			3			3	9	3
	Indicator Score												3
	Hydrant Service Coverage	Within ±50 m service radius		2			2			2		6	2
Open Space	Indicator Score												2
	Total Sub-Variable Score												2.33
	Type of Open Space	Park / field / plaza			3		2			2		7	2.33
	Indicator Score												2.33
	Function of Open Space	Evacuation / fire truck staging / buffer zone			3		2			2		7	2.33
	Indicator Score												2.33
	Size of Open Space	Adequate capacity			3			3			3	9	3
	Indicator Score												3
	Total Sub-Variable Score												2.55
	Response Time	< 15 minutes			3			3			3	9	3
Fire Station Accessibility	Indicator Score												3
	Coverage Area	1 station per 3 subdistricts		2			2			2		6	2
	Indicator Score												2
	Service Radius	2.5 km from the nearest fire station; 3.5 km from its service coverage area			3		2				3	8	2.67
	Indicator Score												2.67
	Accessibility	Traffic, land use, road access			3			3			3	9	3
	Indicator Score												3
	Total Sub-Variable Score												2.67
	Communication Type	Mobile phones and digital communication tools, etc.			3			3			3	9	3
	Indicator Score												3
Communication Facilities	Reporting Ease	Availability of accessible communication channels			3			3			3	9	3
	Indicator Score												3
	Reporting Speed	Preparedness of residents to report fire incidents (procedural knowledge and training experience)			3			3			3	9	3
	Indicator Score												3

	Speed of information flow and coordination among relevant stakeholders			3			3			3	9	3
	Indicator Score											3
Reporting Flow	Clear reporting procedures			3			3			3	9	3
	Indicator Score											3
	Total Sub-Variable Score											3
	Overall Site Infrastructure Effectiveness Score											2.49

NA = Not Available, ANC = Available but Not Compliant AC = Available and Compliant P = Poor, F = Fair, G = Good

NC = Not Compliant, PC = Partially Compliant, C = Compliant

Effectiveness Classification: 1.00–1.67 = Ineffective, 1.68–2.34 = Moderately Effective, 2.35–3.00 = Effective

After the assessment of all site infrastructure parameters, indicators, and sub-variables was completed, a score recapitulation was conducted to determine the effectiveness level of each research component. The recapitulation provides an overview of the effectiveness category of each sub-variable, allowing the identification of components that have met the required criteria and those that still require improvement. The results of the assessment recapitulation are presented in Table 4.

Table 4: Effectiveness Level of Site Infrastructure in Sei Rengas Permata Subdistrict

Site Infrastructure Components	Score	Category
Building Layout and Orientation	2,72	Effective
Building Spacing	2,33	Quite Effective
Neighborhood Access Road	2,83	Effective
Water Sources	2,08	Quite Effective
Yard Hydrant	2,33	Quite Effective
Open Space	2,56	Effective
Fire Station Accessibility	2,67	Effective
Communication Facilities	3,00	Effective
Average	2,49	Effective

Based on Table 4, the effectiveness level of site infrastructure in Sei Rengas Permata Subdistrict obtained an average score of 2.49, which is categorized as effective. This result indicates that most site infrastructure components have supported the implementation of the environmental fire protection system, although several aspects still require improvement (Table 4).

The component with the highest score was communication facilities, with a score of 3.00. Observation and interview results indicate that the community has utilized mobile phones as the primary medium for fire reporting and has understood the reporting procedures to relevant authorities. The availability of easily accessible telecommunication networks also supports rapid information delivery, making communication facilities one of the components with the highest effectiveness level.

Furthermore, neighborhood access roads (2.83), building layout and orientation (2.72), fire station accessibility (2.67), and open spaces (2.56) were also categorized as effective. The neighborhood access roads in the study area generally have adequate widths, relatively good surface conditions, and interconnected circulation routes across most residential blocks. The building layout, which follows the road network, facilitates building identification and access to the area, while fire station accessibility is supported by a response time of approximately 10–11 minutes and the location of the area remaining within the operational service coverage. Meanwhile, open spaces are available in the form of school fields, church courtyards, and neighborhood parks that can be utilized according to emergency needs.

Meanwhile, building spacing (2.33), yard hydrants (2.33), and water supply sources (2.08) remain within the moderately effective category. These values indicate that the three components are available within the study area; however, their conditions and distribution have not fully met the service requirements throughout the entire settlement. In several parts of the residential area, buildings are still arranged with relatively limited spacing, while hydrants are only available at specific locations with limited-service coverage. In addition, water supply sources are still predominantly dependent on the PDAM network, while alternative water sources and specific management systems for firefighting purposes have not been adequately provided. This condition results in an uneven capacity of water supply for firefighting activities across the area.

Overall, the evaluation results indicate that Sei Rengas Permata Subdistrict has an effective level of site infrastructure performance, characterized by the dominance of components classified as effective. Nevertheless, the study also identifies several components that require further attention, particularly related to water supply provision, equitable distribution of yard hydrants, and building spacing regulation. These three components represent the aspects that most influence the improvement of the environmental fire protection system and should become priorities in developing infrastructure strategies for residential areas.

3.3. Relationship between Site Infrastructure and the Effectiveness of the Environmental Fire Protection System in Sei Rengas Permata Subdistrict

After analyzing the existing conditions and evaluating the effectiveness level, the next stage was to identify the relationship between each site infrastructure component and the effectiveness of the environmental fire protection system in Sei Rengas Permata Subdistrict. The analysis was conducted through the interpretation of observation results, interviews, documentation, and effectiveness assessments to explain how each component influences fire prevention, fire spread control, firefighting access, and emergency response processes (Table 5).

Table 5: Relationship between site infrastructure components and environmental fire protection system effectiveness

Components	Contribution to Environmental Fire Protection System Effectiveness
Building Layout and Orientation	An organized building layout facilitates the identification of fire incident locations, accelerates firefighter access, and supports the evacuation process for residents. Conversely, irregular building arrangements may complicate the identification of fire locations and delay emergency response processes [18].
Building Spacing	Insufficient building spacing increases the potential for fire propagation through heat radiation and direct contact between buildings. In contrast, wider spacing or the presence of separation elements can slow down fire spread, providing more time for firefighting operations [19][20].
Neighborhood Access Road	Adequate road conditions accelerate the mobilization of firefighting vehicles and facilitate the distribution of firefighting equipment [21][22]. Obstacles such as illegal parking, protruding buildings, or utility infrastructure blocking access routes may potentially delay response time during fire incidents [5][23].
Water Sources	The availability of water sources determines the continuity of firefighting operations. Limited water supply may hinder firefighting activities, particularly when fires persist for a long duration or involve extensive areas [24].
Yard Hydrant	A well-distributed hydrant system facilitates faster water access for firefighters, thereby improving firefighting efficiency. Conversely, limited hydrant availability requires firefighters to seek alternative water sources, which may delay fire suppression efforts [20].
Open Space	Open spaces function as temporary evacuation areas, fire truck staging areas, community assembly points, and separation zones that help reduce the potential spread of fire to surrounding buildings [25][14][4][21].
Fire Station Accessibility	A shorter travel time to the incident location enables faster firefighting response, increasing the possibility of controlling fire spread. Traffic conditions and road network characteristics also influence firefighter response speed [5][26].
Communication Facilities	Accessible communication facilities accelerate information delivery to firefighters, allowing initial response actions to be carried out promptly. Delays in reporting may cause fires to develop into larger incidents before firefighting operations begin [27][28][29].

Based on Table 12, the effectiveness of the environmental fire protection system is the result of the integration of all site infrastructure components that function in a complementary manner within a residential area. Each component plays a distinct role, ranging from supporting fire emergency accessibility and controlling fire spread to facilitating evacuation and coordination during emergency situations. Therefore, the effectiveness of the environmental fire protection system is not determined

by a single component but by the overall condition and performance of all components as an integrated system.

The results of observations and interviews indicate that the relationships among site infrastructure components are mutually influential in supporting fire emergency response. For instance, neighborhood access roads with good physical conditions and adequate accessibility may not optimally support firefighting operations if water supply sources and hydrant availability remain limited. Likewise, relatively rapid firefighter response times may not sufficiently reduce fire impacts when building spacing is inadequate, allowing fire to spread more easily to adjacent structures. These findings demonstrate that improving the effectiveness of the environmental fire protection system requires the integrated support of all site infrastructure components.

The findings of this study are consistent with [31], who stated that an effective fire protection system is established through the integration of various supporting elements within the built environment. Furthermore, effectiveness fundamentally reflects the extent to which a system achieves its intended objectives, where a higher level of achievement indicates a more effective system [32]. [33] also explained that the effectiveness of a fire protection system is strongly influenced by the availability of adequate facilities and infrastructure, compliance with technical design standards, and the implementation of continuous maintenance practices.

Overall, the analysis indicates that site infrastructure is closely related to the effectiveness of the environmental fire protection system in high-density residential settlements. Therefore, efforts to improve the effectiveness of the fire protection system should be implemented through an integrated approach by addressing components that still have limitations, thereby enhancing area preparedness, accelerating emergency response, and improving the area's capacity to minimize fire risks and impacts.

4. CONCLUSION

The findings indicate that the site infrastructure conditions in Sei Rengas Permata Subdistrict generally support the implementation of the environmental fire protection system in high-density residential settlements. This is demonstrated by the building layout and orientation that relatively follow the road network, neighborhood access roads with adequate pavement conditions and accessibility, the availability of open spaces, fire station accessibility that remains within the service coverage area, and communication facilities supported by the use of mobile phones. However, several limitations were identified in the components of building spacing, water supply sources, and yard hydrants, particularly regarding building density, limited alternative water sources, and the uneven distribution of hydrants throughout the study area.

The evaluation results show that the site infrastructure in Sei Rengas Permata Subdistrict obtained an average score of 2.49 and is categorized as effective. Communication facilities achieved the highest effectiveness score, whereas water supply sources represented the component with the lowest

effectiveness level. These findings indicate that although most components have supported the environmental fire protection system, improvements in water supply provision, yard hydrant availability, and building spacing regulations are still necessary to enhance overall system performance.

The relationship analysis demonstrates that the effectiveness of the environmental fire protection system is influenced by the integration of all site infrastructure components. Building layout, neighborhood access roads, and fire station accessibility contribute to improving accessibility and accelerating fire emergency response. Conversely, inadequate building spacing may increase the potential for fire spread, while limitations in water supply sources and hydrant availability may hinder firefighting operations. Open spaces support evacuation processes and firefighting activities, whereas communication facilities facilitate rapid information dissemination and coordination during emergency situations. Therefore, improving the effectiveness of the environmental fire protection system requires an integrated approach to site infrastructure development, enabling each component to complement one another in reducing fire risks and impacts in high-density residential settlements. This study has several limitations. First, it was conducted in only one study area; therefore, the findings cannot yet represent the overall condition of environmental fire protection systems in all high-density residential settlements in Medan City or other regions. Second, the analysis was limited to site infrastructure components and did not consider community behavior, fire management policies, or quantitative fire risk simulations. Future studies are recommended to examine multiple high-density residential areas with different characteristics and to integrate physical, social, and policy-related aspects into the assessment of environmental fire protection systems. Such an approach is expected to provide a more comprehensive understanding of the factors influencing fire protection system effectiveness and to support the development of more appropriate and sustainable fire mitigation strategies.

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