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Site Selection Study of Siren Early Warning System for Community Preparedness due to Potential Dam Calamity: Case Study of Kg Batu Melintang, Jeli, Kelantan

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Abstract. Effective early warning systems (EWS) for dam disasters rely heavily on the strategic placement of sirens to ensure comprehensive coverage and timely alerts. This study investigates the criteria and methodologies for optimizing siren placement, utilizing Geographic Information System (GIS) technology and multi-criteria decision analysis. By integrating data on population density, geographic features, and flood hydrodynamics, the study identifies optimal siren locations to maximize effectiveness. Population data from recent census reports, geographic data from topographic maps and satellite imagery, and disaster simulation data were analysed to determine high-risk areas and prioritize siren placement. The results demonstrate that strategic placement of sirens with standard coverage radius of up to 1 kilometre can significantly enhance early warning capabilities, even in areas prone to flooding, provided they are strategically placed in densely populated zones. The findings highlight the importance of data-driven site selection in improving disaster preparedness and risk management strategies, ultimately contributing to more effective early warning systems that safeguard lives and property in vulnerable communities.

1.Introduction

Dam disasters, often triggered by structural failures, overtopping, or sudden releases of water, pose significant threats to downstream communities, leading to catastrophic flooding [1]. These floods can occur with little warning, overwhelming local infrastructure and causing widespread devastation. The magnitude of such disasters is often staggering, with the potential to inundate large areas within minutes, leaving little time for evacuation [2]. The impact on affected populations can be severe, resulting in loss of life, displacement of communities, destruction of property, and long-term economic consequences.

Historically, dam failures have resulted in some of the deadliest flood events, highlighting the vulnerability of populations living downstream. For instance, the failure of the Banqiao Dam in China in 1975 led to an estimated 171,000 deaths [3] while the more recent collapse of the Brumadinho Dam in Brazil in 2019 caused significant casualties and environmental damage [4]. These disasters underscore the importance of robust disaster preparedness measures, particularly in regions where large populations reside in flood-prone areas downstream of dams.

Given the high stakes, the necessity for an effective early warning system (EWS) becomes paramount. An EWS can provide critical lead time for at-risk communities, allowing for timely evacuations and the activation of emergency response plans [5]. By integrating real-time monitoring of dam conditions with predictive flood modelling, EWS can significantly reduce the risk to human life and minimize the damage to property and infrastructure. The ability to issue timely and accurate alerts is essential for saving lives and mitigating the devastating impacts of dam-related floods.

However, the effectiveness of an EWS is not solely dependent on its technological capabilities; the proper selection of sites for deploying warning mechanisms, such as sirens, is equally crucial. Strategic placement ensures that alerts reach the maximum number of people in the shortest possible time, especially in densely populated or geographically complex areas. Improper site selection can lead to gaps in coverage, delayed warnings, and increased vulnerability of certain communities [6]. Therefore, incorporating geographic, demographic, and predictive flood coverage into the site selection process is essential to optimizing the performance of early warning systems and ensuring comprehensive protection for all at-risk populations.

This paper presents a study on the site selection process for siren early warning systems, focusing on a combination of geographic information system (GIS) technology and multi-criteria decision analysis. The objective is to develop a methodology for identifying optimal sites that maximize the reach and effectiveness of sirens in dam disaster-prone areas. A case study for site selection and installation of an early warning system at Pergau Dam downstream population is demonstrated.

Dixon et al. (2022) utilized GIS to assess coverage areas for siren placement, highlighting the importance of spatial analysis in optimizing coverage [7]. Rahmati et al. (2019) incorporated multi-criteria decision analysis to evaluate multiple criteria such as population density, proximity to hazard zones, and cost-effectiveness [8]. Their findings suggested that a multi-criteria approach could significantly improve the decision-making process for site selection. However, there remains a need for integrated approaches that combine multiple data sources and analytical techniques to enhance decision-making. This study aims to address this gap by proposing a holistic methodology for siren site selection that leverages GIS and multi-criteria decision analysis.

1.1 Early Warning System Site Selection Development

Numerous approaches for early warning system site selection have been investigated in earlier research. Munro-stasiuk (2006) underlined the significance of spatial analysis in maximizing coverage by using GIS to evaluate coverage regions for siren placement [9]. Multi-criteria decision analysis was used by Goto & Murray (2020) to assess factors like cost-effectiveness, population density, and proximity to danger zones [10]. Their results indicated that the process of choosing a site might be considerably enhanced by using a multi-criteria approach. To improve decision-making, integrated strategies that incorporate various data sources and analytical methods are still required. By putting forth a comprehensive technique for siren site selection that makes use of multi-criteria decision analysis and GIS, this work seeks to close this gap.

1.1.1 Criteria for Site Selection

The selection of optimal sites for siren placement is guided by several key criteria designed to maximize the effectiveness of early warning systems in the event of a dam disaster. First and foremost, population density is a critical factor; areas with higher population densities are prioritized to ensure that the maximum number of people can be reached by the sirens. The underlying assumption is that these densely populated regions have a greater need for immediate alerts during emergencies to facilitate swift evacuations and minimize casualties.

Additionally, geographic features play a significant role in determining the placement of sirens. Topographic elements such as hills, valleys, and urban structures can influence how sound propagates through an area, potentially creating zones where the siren's sound might be blocked or diminished. Therefore, understanding the local terrain is essential to ensure that the sirens' sound coverage is effective and consistent, reaching all intended areas.

Finally, flood hydrodynamic analysis data is used to further refine site selection. By analysing the area's most likely to be affected by flooding through numerical flood simulations, high-risk zones can be identified and prioritized for siren placement. This ensures that the early warning system is strategically positioned to alert those in the path of potential floods, thereby enhancing the overall effectiveness of disaster preparedness and response efforts.

1.1.2 Analytical Tools and Techniques

Analytical tools and techniques play a crucial role in the selection and optimization of siren placement for early warning systems in dam disaster scenarios. One of the primary tools used is Geographic Information System (GIS) technology. GIS is instrumental in performing spatial analysis and visualizing various data layers that are essential for decision-making. By integrating and analysing spatial datasets, GIS provides a detailed visual representation of potential siren sites and their corresponding coverage areas. This enables planners to identify gaps in coverage, assess the impact of geographic features on sound propagation, and make informed decisions about where to place sirens for maximum effectiveness.

In addition to GIS, multi criteria decision analysis is employed to evaluate and rank potential siren sites based on a set of predefined criteria. multi criteria decision analysis involves assigning weights to each criterion, reflecting its relative importance in the decision-making process. These weights are then used to score and rank each potential site, allowing for a systematic comparison of different options. By combining GIS for spatial analysis and multi criteria decision analysis for decision-making, the site selection process becomes both data-driven and aligned with the strategic priorities of ensuring comprehensive coverage and effective early warning capabilities

1.1.3 Data Collection and Processing

Data collection and processing are critical steps in ensuring that the site selection for siren placement is based on accurate and relevant information. The first major data source is population data, which is typically sourced from the latest census reports. This data provides detailed information on population distribution across the study area, allowing for the identification of densely populated regions that should be prioritized for siren placement to ensure maximum coverage and effectiveness.

Next, geographic data is gathered from topographic maps, satellite imagery and if available, latest aerial map. This data offers valuable insights into the physical landscape, including natural features like hills and valleys, as well as urban structures that could impact the propagation of sound. Understanding the geographic context is essential for determining how effectively siren sounds will travel across different terrains, ensuring that no areas are inadvertently left unprotected.

Finally, disaster simulation data is compiled from various sources and studies, providing critical information on potential disaster events, such as dam breaches, and their likely impacts. This data includes flood modelling and other predictive analyses that help to identify high-risk zones where sirens are most needed. By processing and integrating these diverse datasets, the site selection process becomes more robust, ensuring that the early warning system is strategically positioned to maximize its effectiveness in protecting vulnerable populations.

The data were processed and analysed using GIS software, which allowed for the overlay and spatial analysis of multiple datasets. Multi criteria decision analysis was performed using manual calculations to evaluate and rank potential sites.

2. Methods & Development: Case Study in Kg Batu Melintang, Jeli

Kampung Batu Melintang is a rural village situated in the Jeli District of Kelantan, Malaysia, located downstream of the Pergau Dam. The village is predominantly inhabited by Malay families who primarily engage in agriculture, including the cultivation of rubber, palm oil, and various crops [11]. The population density is relatively low, and the community is characterized by a blend of traditional lifestyles and modern influences. Residential structures range from traditional wooden houses to more contemporary concrete buildings, reflecting the region's development over time.

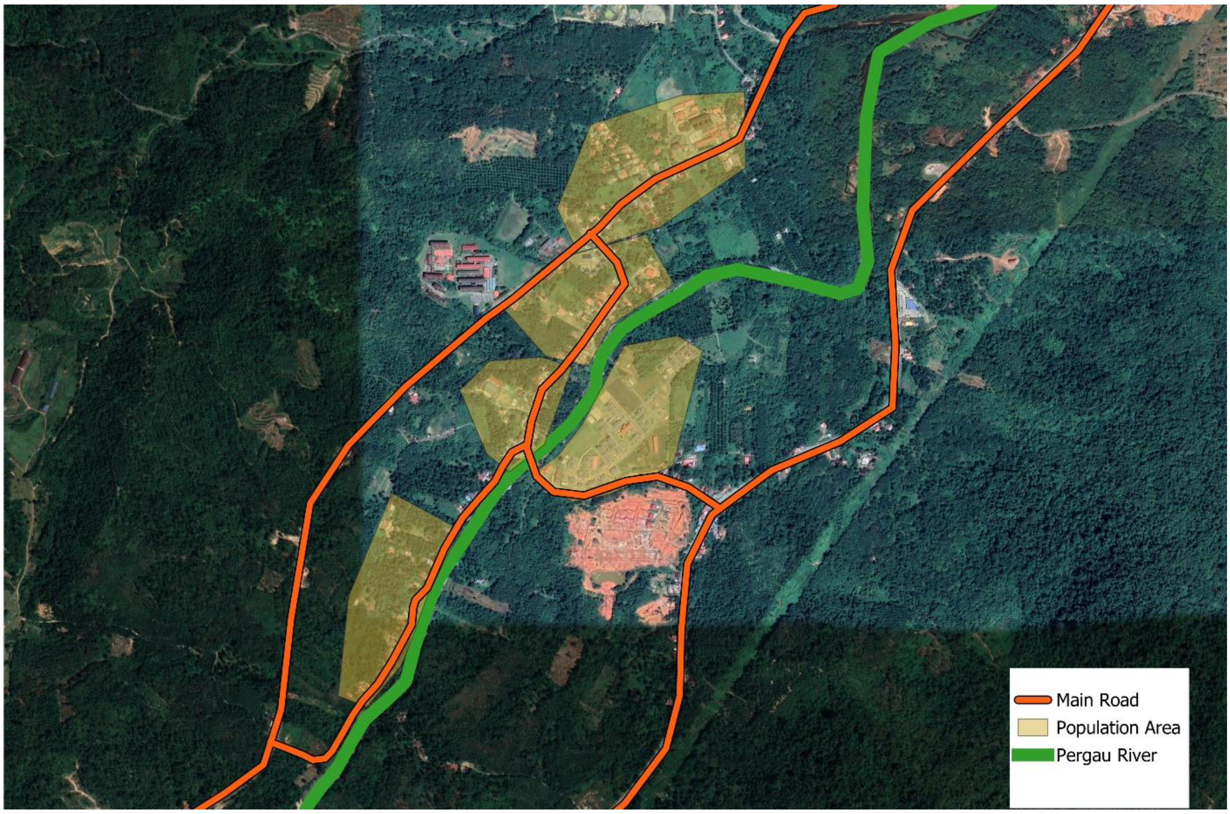

Figure 1. Layout of Kg Batu Melintang, Jeli

The village infrastructure includes essential amenities such as schools, healthcare centres, and local markets, with a reasonably developed road network providing connectivity to nearby towns and cities. Social cohesion is a notable feature of Kampung Batu Melintang, with community events and religious activities playing a central role in daily life. Given its geographical location, the village is potentially vulnerable to flooding and other dam-related disasters, making it crucial to implement an effective early warning system tailored to the specific needs and capacities of its residents. Understanding the village's infrastructure, communication channels, and community response mechanisms is vital for designing a robust early warning system that can mitigate risks and enhance the safety of the downstream population. The method of selection for siren location is carried out according to the proposed methodology detailed out in section 1.1 earlier.

2.1 Population Density

In 2010, the population of Kg Batu Melintang was recorded at 8,456 individuals, comprising 4,419 males and 4,037 females. The ethnic composition of the village was predominantly Malay, with 8,327 individuals identifying as such. Additionally, there were 13 Chinese residents, 2 Indian residents, and 7 individuals from other ethnic backgrounds (Department of Statistics Malaysia, 2010). The entire population is well distributed over five (5) densely populated areas which laid along Pergau river mostly on the left bank. The distribution is believed due to the flat area and easy access to Pergau river for daily activities on the earlier days. However, at the same time, the population are easily exposed to potential flood in the event of disaster.

2.2 Geographic Features
village is nestled within a lush, tropical landscape typical of Malaysia, with dense vegetation and a variety of flora and fauna. The terrain is generally hilly, contributing to a scenic view of rolling hills and valleys. Additionally, the area is interspersed with small rivers and streams, which are vital for local agriculture and provide picturesque natural beauty. The climate is tropical, with consistent temperatures and significant rainfall throughout the year, supporting the rich biodiversity and fertile soil that are integral to the village's agricultural practices.

2.3 Flood Hydrodynamic Analysis
Due to the distribution of the populated area being close to the rivers, a substantial portion of the village is at high risk in the event of flooding. Studies carried out previously by Mamat et al. (2023) have shown that numerical modelling of flood hydrodynamic analysis predicts that the potential impact of a dam failure would result in flooding that affects up to 95% of the entire population [5]. The only exception to this would be the school buildings, which are situated on higher ground and thus remain outside the predicted flood coverage area.

3. Results & Discussion

Multi criteria decision analysis carried out shows that site C are the most suitable area for installation of siren. This is done through the weightage assigned for each element and the combination of several weightages has finally revealed site C to be the best for siren installation. Table 1 summarizes the key elements of each site, including population coverage and proximity to high-risk zones, and the elevation of the site.

Table 1. Key elements potential siren locations

Site ID	Population	Distance to Hazard (m)	Elevation (MSL)
A	1,203.00	200	95
B	1,458.00	50	94
C	3,557.00	50	92
D	525.00	60	92
E	1,713.00	40	90

Table 2 shows the summary of weightage for each element and the final score. The summary of result from multi criteria decision analysis demonstrated in table 2 shows that the site with the highest score provide extensive coverage, with a significant proportion of the population within audible range of the sirens. Having the highest in population size, it also situated close to the source of hazard which is the river, and the area also located at low elevation. These factors contribute to the highest score of the area.

Table 2. Summary of weightage for each element and the final score

Site ID	Population	Weightage A	Distance to Hazard (m)	Weightage B	Elevation (MSL)	Weightage C	Score (Weightage A x B x C)
A	1,203	2	200	2	95	1	4
B	1,458	3	50	3	94	2	18
C	3,557	7	50	5	92	3	105
D	525	1	60	1	92	3	3
E	1,713	3	40	4	90	4	48

3.1 Flood Hydrodynamic Analysis

Figure 2 presents the flood hydrodynamic analysis for the potential failure of the Pergau Dam, utilizing historical hydrology data and details of the Pergau Reservoir storage area. The analysis shows flood coverage area depicted in light blue. The critical takeaway from this analysis is the identification of areas at risk, particularly those with dense populations, which are crucial for prioritizing evacuation plans and deploying early warning systems.

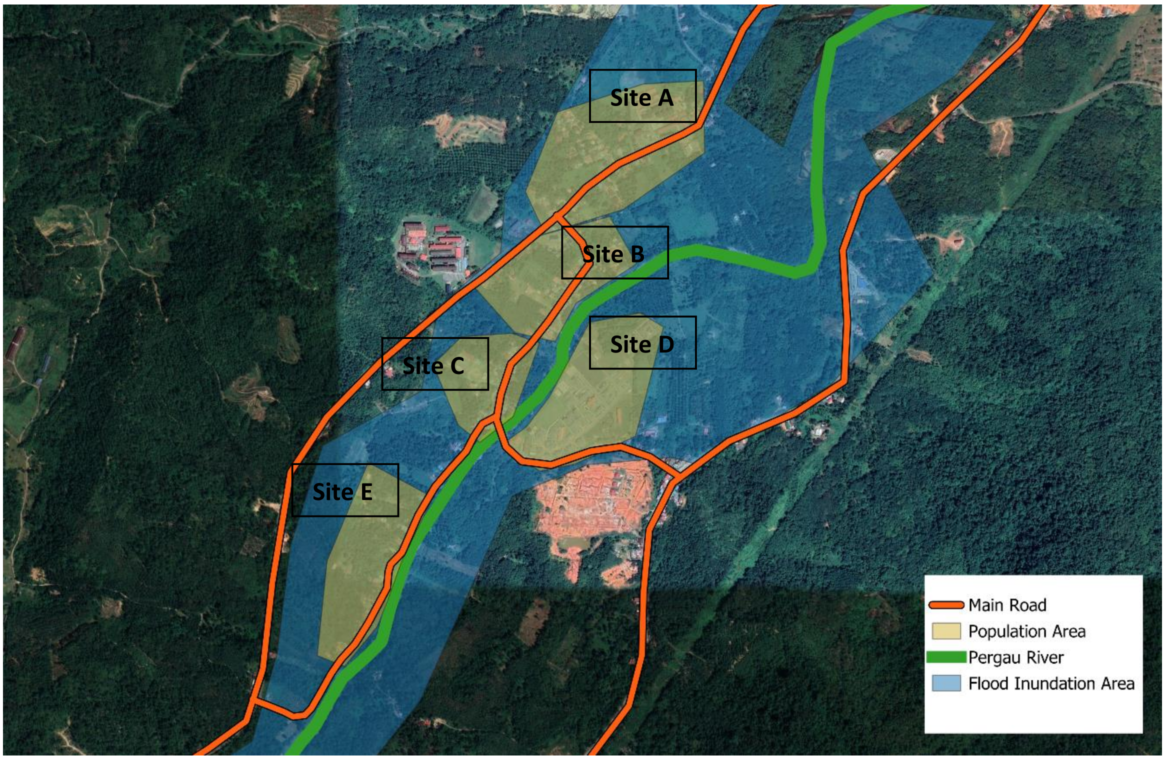

Figure 2. Flood hydrodynamic analysis showing affected area due to potential dam failure

The map in Figure 2 indicated that Pergau river flows in the middle of the map from southwest to the northeast. Two main roads lie alongside of the river on the right bank and on the left bank. There are five (5) main populated areas in Kg Batu Melintang with a total of 8,456 people residing the area. With the simulation overlaid on the populated area, it is clear that that the entire population could be affected by the potential flood of unlikely event of dam failure.

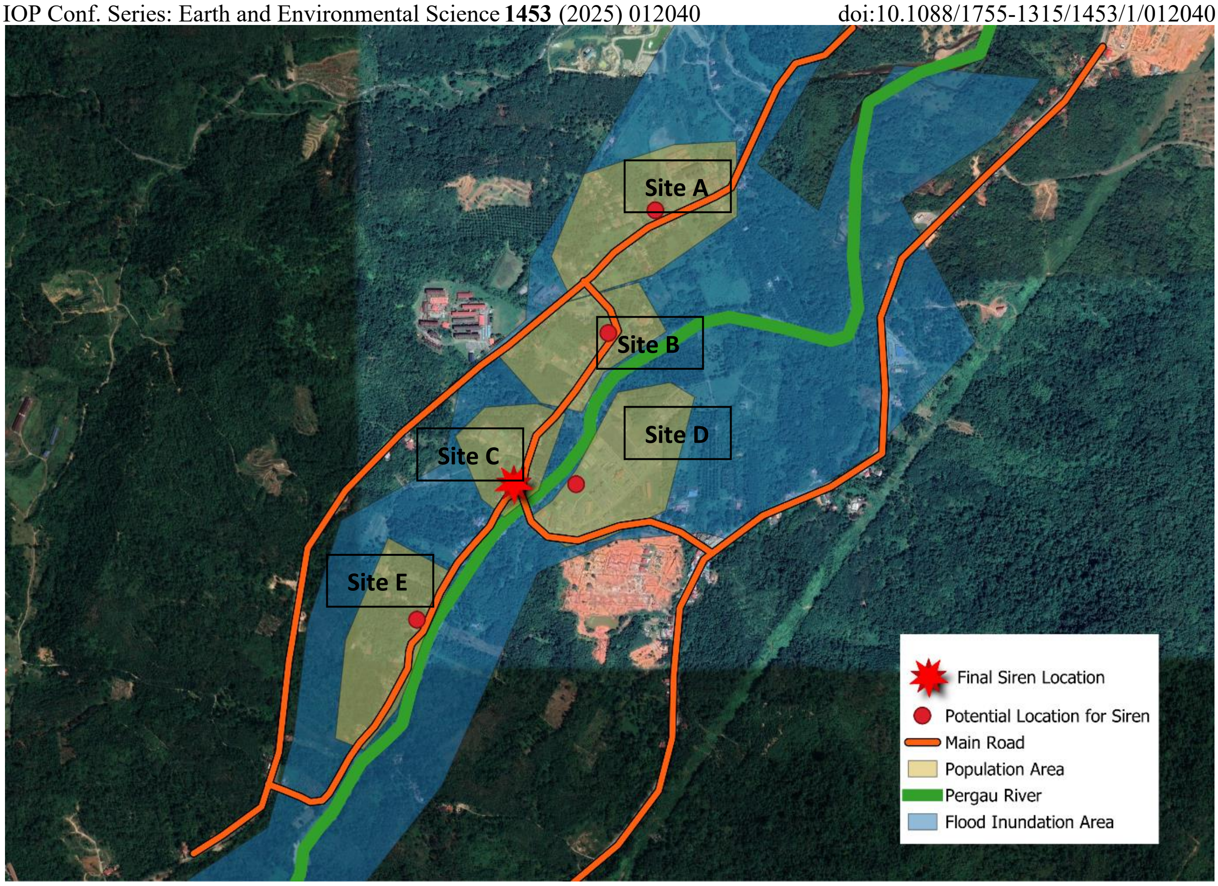

Figure 3. Potential locations for installation of siren and the final location of siren

In Figure 3, several locations have been identified as potential sites for siren installation, with focus on densely populated areas. However, budgetary constraints necessitate prioritizing the most critical locations. Following a comprehensive multi-criteria decision analysis, Site C has been determined as the optimal location for the installation

The placement of siren has carefully considered the siren coverage area, population density, and potential flood zones. Widely used warning sirens have the capacity to effectively cover a radius of up to one(1) kilometre. Figure 3 shows the proposed siren locations as indicated on the map to ensure that these critical devices are strategically positioned. While some proposed sites may fall within potential flooding areas, the ability of the sirens to operate effectively before a disaster occurs justifies their placement in these zones. The selected sites within a 1-kilometer radius are chosen because they represent areas with the highest population density and the greatest number of residents. This ensures that the sirens will provide timely alerts to the largest number of people, thereby maximizing the effectiveness of the early warning system.

4. Conclusion

In conclusion, the strategic placement of sirens is a critical component of an effective early warning system for dam disasters. By considering key factors such as siren coverage area, population density, and potential flood zones, the proposed sites ensure that alerts are delivered to the highest number of residents in the most vulnerable areas. The integration of detailed geographic and demographic data into the site selection process allows for a targeted approach that enhances the overall efficiency of the early warning system. Despite some sirens being located in potential flood zones, their placement is justified by their capacity to operate prior to disaster events, thus providing timely warnings and facilitating prompt evacuations. Ultimately, these measures contribute significantly to reducing risk, improving disaster preparedness, and safeguarding lives and property in at-risk communities. The approach demonstrated in this study underscores the importance of data-driven decision-making in disaster management and sets a benchmark for future early warning system implementations.

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