



## An Optimal Solution for Locating Tide Station Locations in Historic Bay of Thailand by Using Location Allocation Models (P – median)

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Received: April 18, 2025

Revised: June 6, 2025

Accepted: June 20, 2025

### Abstract

The aim of this study is to utilize a location allocation model (P-median) to determine the optimal locations for tide stations in the Historic Bay of Thailand, based on three factors: variation in tide elevation, the number of ports, and population density. Two scenarios were considered: (1) adding new tide stations while retaining all existing ones; and (2) not retaining the existing tide stations but instead rearranging and adding new stations. The results indicated that the second scenario—rearranging the tide stations and adding new ones without retaining the existing stations—provides a more optimal long-term solution in terms of budget efficiency and coverage. This study can serve as a guideline for hydrographic offices to adopt when planning the construction of tide stations.

**Keywords:** Location Allocation Model, P-median, Tide Stations, GIS

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## 1. Introduction

Tides are the phenomenon that the body of water rises and falls due to gravitational interactions between Sun, Moon, and Earth [1]. Tide is a crucial factor that mariners and coastal residents must consider. For mariners, without adequate and accurate tidal information, a ship can get ground due to sailing to a shallow area during low tide periods. Hence, navigation and tidal information is not separatable. Moreover, people who live along shorelines are also relying on tide information since several activities must be related to the sea, so lacking this information can lead to undesirable outcome especially for fishery, tourism business, and hydrographic survey.

As tide information is necessary, tide stations are constructed along shorelines to measure and predict tides see figure 1. Based on the tide station location standard, tide stations are required every 10 nautical miles along the shoreline (18,520 kms.) to derive adequate and accurate tide information [2]. However, it is crucial to note that tide stations cannot be set up arbitrarily. It is necessary to ensure that a tide gauge pressure sensor should not dry out, so a tide station location should be chosen ports or other offshore constructions [2].

Since Historic Bay of Thailand is one of Thailand's most significant marine regions, because there are numerous ports and marine communities as well as tourist destinations, but there are only 9 existing tide stations along the coastline as shown in figure 2 that do not cover all areas based on the standard of International Hydrographic Organization (IHO).

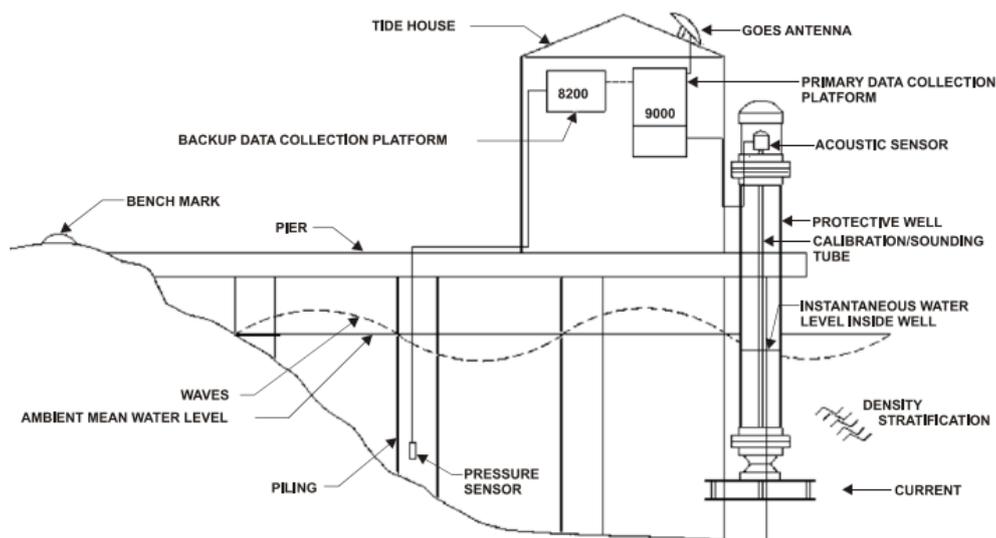


Figure 1 Water Level Measurement System [1]

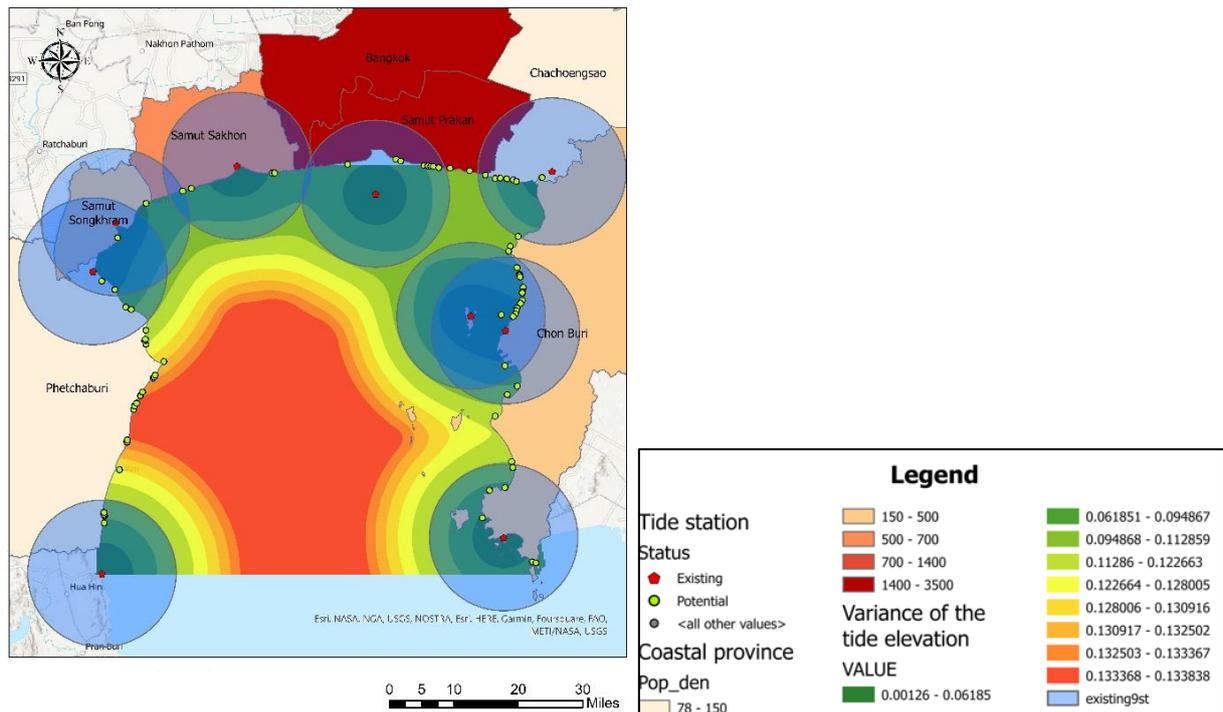
The above-mentioned problem can be addressed by employing the fundamental of a location-allocation model, especially the P – median models. The P– median method can provide a solution to this issue while also taking into consideration the characteristics of each demand point. The P -median method aims to “locate a multiple number of facilities and allocation the demand served by these facilities so that the service is as efficient as possible” [3].

P – median model has been utilized in various cases to locate facilities or services to meet demands. For instance, it has been applied in locating bicycle-sharing programs and air pollution monitoring network [4]. Therefore, the P – median model is deemed suitable for finding optimal solution for locating facility to meet demands. However, no study has utilized P – median model to arrange tide station locations before. Hence, it is intriguing to apply the P – median model in this study.

Given the identified problem and the capabilities of the P-median model, this study aims to utilize the P-median model to determine optimal tide station locations that fully cover the Historic Bay of Thailand. Two scenarios are considered: (1) adding new tide stations while retaining all existing ones; and (2) not retaining the existing tide stations but instead rearranging and adding new ones. The goal is to determine the best solution based on spatial coverage and financial considerations.

## **2. Literature Review**

Tide stations play a crucial role in various aspects. Undoubtedly, tide information is directly associated with navigation safety in the water, as depth values indicated on a nautical chart must be adjusted with tide elevations to determine the actual depth. For example, the Thai nautical chart number 112 employs the lowest low water as the vertical reference, as depicted in figure 3 [5]. The lowest low water value is derived from the minimum tide elevations in a tide cycle.



**Figure 2** Existing Tide Stations and Potential Locations for Being Tide Stations in Historic Bay of Thailand

That takes 18.6 years [2], signifying the necessity of a tide station to establish the vertical reference for creating such maps. Furthermore, consider a scenario where a ship with a 7-meter draft is navigating to an area within the red circle, indicating a depth of 5.4-meter from the lowest low water. If the tide elevation value from the tide table is 2 meters, the sailor may believe the depth to be  $5.4 + 2 = 7.4$  meters, as shown in figure 3. However, if the tide station used to generate the tide table is located more than 10 nautical miles away from this area, the actual tide elevation may be only 1 meter. Consequently, the real depth in this area is only 6.4-meters. This discrepancy highlights the importance of accurate tide information for navigation safety, as an error in such information could lead to a ship running aground. This example vividly illustrates the critical role of tide information in ensuring the safety of navigation.

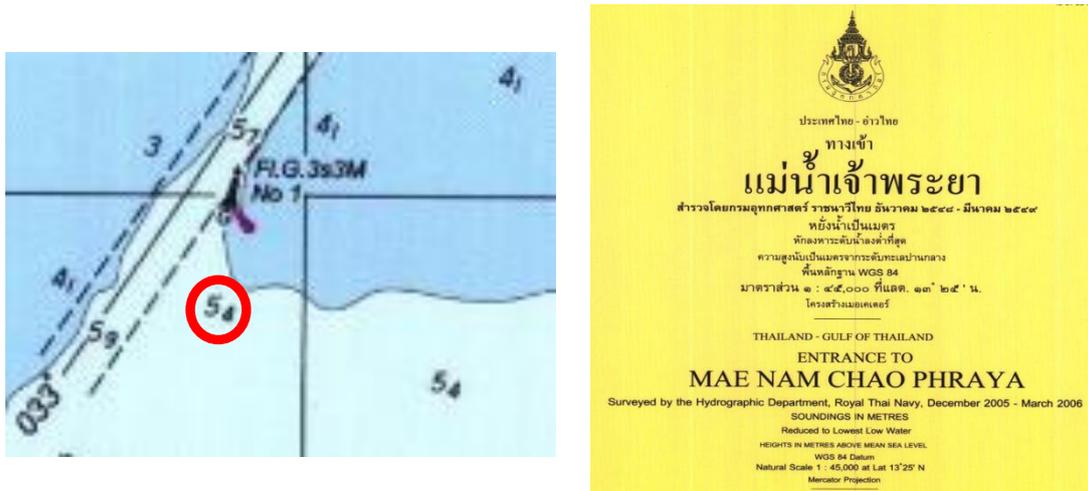


Figure 3 Water Depth in Entrance to Chao Phraya River [5]

Not only are tide stations essential for seafarers, but they are also crucial for hydrographers. As is widely known, all surveys must refer to a horizontal reference (datum WGS-84) and vertical reference (Mean Sea Level). Similarly, Hydrographic Department of Royal Thai Navy (HDRTN) utilizes the lowest low water as vertical reference for creating nautical charts (HDRTN). Therefore, it is imperative to have a tide station in the survey area, and if not available, temporal tide station must be set up [2]. Figure 2 illustrates that there are substantial areas not covered by existing tide stations in the study area, particularly in the west. Consequently, if the HDRTN needs to resurvey a chart on the western side of the study area, numerous temporal tide stations would need to be established, making hydrographic survey missions more challenging. Hence, strategically distributing tide stations is more advantageous.

Furthermore, tides and currents are interconnected, and current plays a crucial role in various activities such as diving, water sport, and fishery. As depicted in figure 4, the water current symbol (in the red circle) indicates that during a flood tide, the water current flows eastward at 1.1 knots, and the water current flows westward at 0.5 knots during an ebb tide. This information is significant for divers, as diving in strong currents is generally undesirable. Similarly, tourists may not enjoy water sports when the current is too strong. Therefore, tide stations serve as a source of tide information that supports various activities. Inadequate and inaccurate tide information might impact on the examples above, leading to unexpected incidents.

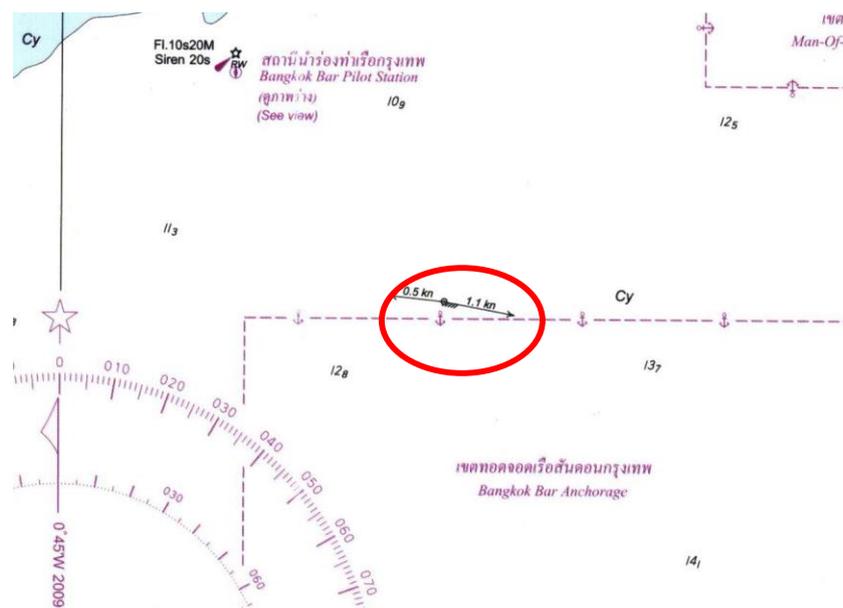


Figure 4 Water Current in Entrance to Chao Phraya River [5]

### 3. Study Area and Data

#### 3.1 Study area

Historic Bay of Thailand is located inside the Gulf of Thailand covers 7 provinces: Bangkok, Phetchaburi, Samut Prakan, Samut Sakhon, Samut Songkhram, Chon Buri, and Chachoengsao. As depicted in figure 5, the areas with high population density are in the northern and eastern parts of the study area. Currently, there are 9 tide stations belonging to Hydrographic Department of Royal Thai Navy (HDRTN) and Marine Department of Thailand (MDT), as presented in figure 2. In the study area, 75 locations are potentially suitable for setting up tide stations, based on the criteria from the IHO. The Historic Bay of Thailand is vital for Thai economy due to the presence of major ports on the eastern side, such as Leam Chabang Port, Chuk Samet Pier, and Sattahip Naval Base, as shown in figure 5. Additionally, many locations in this area are popular tourist attractions, including Si Chang Island, Lan Island, Cha – am beach, and Pattaya City as illustrated in figure 5. Therefore, the Historic Bay of Thailand is one of the essential marine regions in Thailand, but existing tide stations do not cover all coastlines.

#### 3.2 Data

Most of the information is derived from HDRTN and MDT. Firstly, locations and lowest low water from mean sea level values of existing tide stations were supported by HDRTN and

MDT through the Thai tide table. Also, population of each province was sourced from the Bureau of Registration Administration of Thailand [6] as shown in table 1. Regarding the number of ports for each province, this information was obtained from MDT in 2025, as present in table 1 [7]. Finally, Thai nautical chart number 001 and 112 were provided by HDRTN as background information in this project in ArcGIS Pro [5].



Figure 5 Overall Information in the Historic Bay of Thailand [5]

Table 1 Basic Information of each Province in the Study Area

Provinces	Areas (km <sup>2</sup> )	Population	Population Density (person/km <sup>2</sup> )	Port Number
Bangkok	1,571.371	5,349,004	3,404	28
Chachoengsao	5,165.910	729,140	141	18
Chon Buri	4,504.764	1,613,119	358	24
Phetchaburi	6,183.001	479,448	78	9
Samut Prakan	949.001	1,365,595	1,439	42
Samut Sakhon	856.876	567,024	662	12
Samut Songkhram	414.391	185,095	447	5

## 4. Methods

### 4.1 Pre-processes

Overall, the method of this study can be divided into 3 main processes. The first one is to preprocess the raw data to comply with the requirement of functions in R. Then, R function was used to compute P – median with different scenarios. After that, ArcGIS Pro was used to visualize the results from R and discuss the results.

After deriving 9 locations of existing tide stations from the Thai Tide Table, those locations were plotted in ArcGIS Pro with the coordinate system as WGS 84 UTM Zone 47 N, as shown in figure 2. Then, 75 potential locations for setting tide stations were selected with conditions that a tide station location should be constructed besides ports or any offshore constructions because a tide gauge pressure sensor should not dry out [2]. Hence, all ports and offshore constructions in the study area were chosen to be potential tide-station locations. Next, attribute information was input, including province name, area, population, population density, port number, and variance of tide elevation. Finally, the potential and existing tide station locations were exported in both CSV and shapefile formats to be use in R for P – median models.

### 4.2 Methods

After the raw data was preprocessed to comply with functions in R, P–median functions in R were used to analyze 2 scenarios to derive an optimal solution.

First of all, P – median method was implemented in this study for locating a multiple number of tide stations and allocating the demand served by these tide stations so that the service is as efficient as possible based on equation (1), (2), (3), (4), and (5). Where  $i$  and  $j$  is indices used to refer to a potential tide station location,  $x_{ij}$  is 1 if demand at  $i$  assigns to tide station at  $j$  and is 0 otherwise,  $x_{jj}$  is 1 if a tide station is sited at site  $j$  and serves demand at  $j$  and is 0 otherwise,  $p$  = the number of tide stations that are to be located [3].

$$\text{Minimize } Z = \sum_{i=1}^n \sum_{j=1}^n w_{ij} d_{ij} x_{ij} \quad (1)$$

$$\sum_{j=1}^n x_{ij} = 1 \text{ for each } i = 1, 2, \dots, n \quad (2)$$

$$\sum_{j=1}^n x_{jj} = p \quad (3)$$

$$x_{ij} \leq x_{jj} \text{ for each } i \text{ and } j \text{ where } i \neq j \quad (4)$$

$$x_{ij} = 0, 1 \text{ for each } i \text{ and } j \quad (5)$$

After that, there were 2 main scenarios implemented in the P – median method for this study. Firstly, P – median with using the combination of population density, the number of ports, and variation of tide elevation as weight, so the weight was created by using equation (6) as the variation of tide elevation is affected to the safety of navigation and marine activities more directly, so its weight was higher than others. However, it would be more suitable to use statistical or mathematical methods to indicate weight for each factor in future research. The variation of tide elevation was computed by interpolating the differences between lowest low water and mean sea level for each demand with kriging interpolation. Secondly, P – median with weight as the equation (6), but not forcing existing tide stations was analyzed after that. With these 2 cases, it could be compared between keeping existing tide stations and not keeping them, which one required a minimal number of tide stations in the system. After obtaining the result from R, such results were visualized by ArcGIS Pro for discussion.

$$W_{ij} = \text{Population density}_{ij} + \text{The number of ports}_{ij} + 2 * \text{Variation of tide elevation}_{ij} \quad (6)$$

In terms of coverage of each tide station, although the standard of hydrographic survey mentioned that each tide station can cover area not more than 10 nautical miles [2], the coverage varies depending on local characteristics, especially variation of tide elevation. As such, the radius of each station was computed based on the geometric interval classification with 10 classes from the variance of tide elevation. Thus, an area that has a high variance of tide elevation has a shorter radius of coverage than a low variance area as shown in Table 2. Geometric interval classification is a data classification method commonly used in cartography and geographic information systems (GIS). It is designed to group numeric data into classes (intervals) based on a geometric progression. Therefore, the geometric interval classification function on ArcGIS-Pro software was used to classify variance values in this research.

**Table 2** Criteria for the Radius of each Tide Station

Color	Variance	Radius
	$\leq 0.055291$	10 Nm
	$\leq 0.087424$	9 Nm
	$\leq 0.106534$	8 Nm
	$\leq 0.117899$	7 Nm
	$\leq 0.124658$	6 Nm
	$\leq 0.128677$	5 Nm
	$\leq 0.131068$	4 Nm
	$\leq 0.132489$	3 Nm
	$\leq 0.133335$	2 Nm
	$\leq 0.133838$	1 Nm

After obtaining the results, construction cost and operating cost were used to estimate which solution is the most suitable in terms of financial aspect in the long run.

## 5. Result and Discussion

Since the objective of this study is to use P -median methods to achieve a fully coverage of the locations of the tide stations in the Historic Bay of Thailand, the first scenario is with  $p = 17$  with weight as equation (6) and forcing 9 existing tide stations, as shown in figure 6. From the result, it shows that 4 more new tide stations are added on the western side of the study area to cover all shorelines on the west. This is reasonable as this area shows higher variation in tide elevation. However, there is a small gap in Phetchaburi province.

In the meantime, another 3 new tide stations are added in the north-east of the study area as this area has high population density as well as port numbers. Finally, a new tide station is added to fill the gap in the east, where this area is moderately varied in tide elevation.

The second scenario is  $P = 15$  with weight as equation (6) but not forcing existing tide station as shown in figure 7. The result shows that only 15 tide stations are required to cover all shorelines in the study area. However, no existing tide station is selected in this case.

As can be seen from both results, P – median model assigns more clusters on the areas that have high variation of tide elevation, high population density, and a high number of ports. These can be the guidelines for arranging tide stations systematically and efficiently. Moreover, as each radius of the tide station coverage is changed based on the variance of tide elevation, this makes the model more realistic, because without this logic, a lot of overlaps of coverages occur, and these make the result more illogical, as shown in figure 8.

From the results, if Thailand decides to rearrange existing tide stations and add more 6 new tide station, as shown in figure 7, only 15 tide stations are required to cover all shorelines in the study area. On the other hand, if Thailand keeps 9 exiting tide stations and adds more 8 new tide stations, 17 tide stations in the total are required to cover all coastlines in the study area. However, in order to decide the optimal solution between these scenarios, information about operating cost and construction cost for a tide station is needed, because it can be less expensive for the long term if Thailand has a smaller number of tide station, resulting in operating cost in the future, but it requires a high initial cost for constructing more new tide stations. In contrary, if Thailand decide to operate 17 tide stations in the system, it may need a higher budget in the long run, but it requires lesser budgets at the beginning, because there is no need to rearrange 9 existing tide stations. However, there is no clear estimate construction and operating costs of a tide station in Thailand, so estimate costs of construction and operation from a previous study in another country were used in this study, which were 6,000 USD and 14,000 USD for construction cost and operating cost, respectively [8]. The result is shown in table 3.

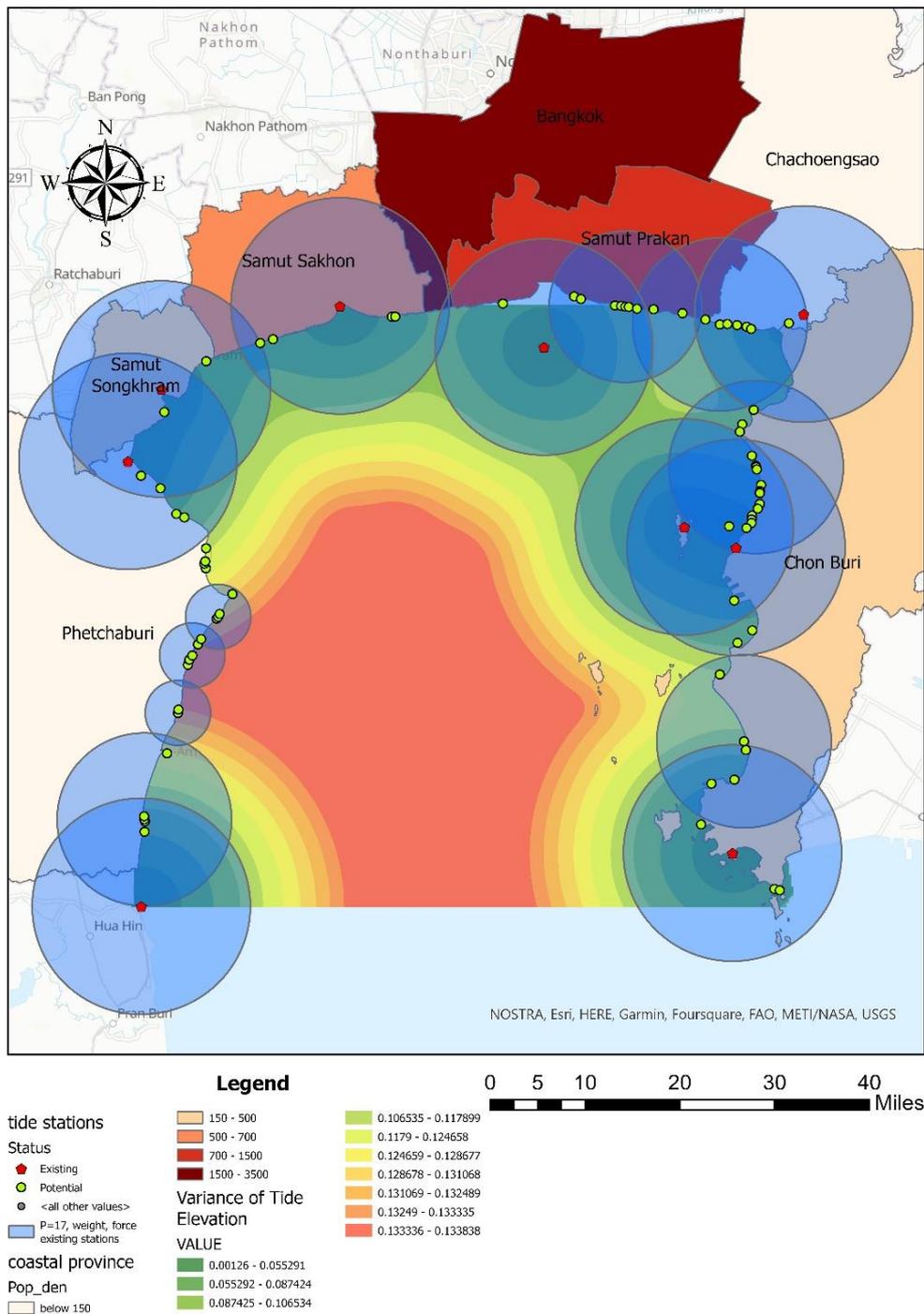


Figure 6 Result from P – median, P = 17, Weight, Forcing Existing Tide Stations [5]

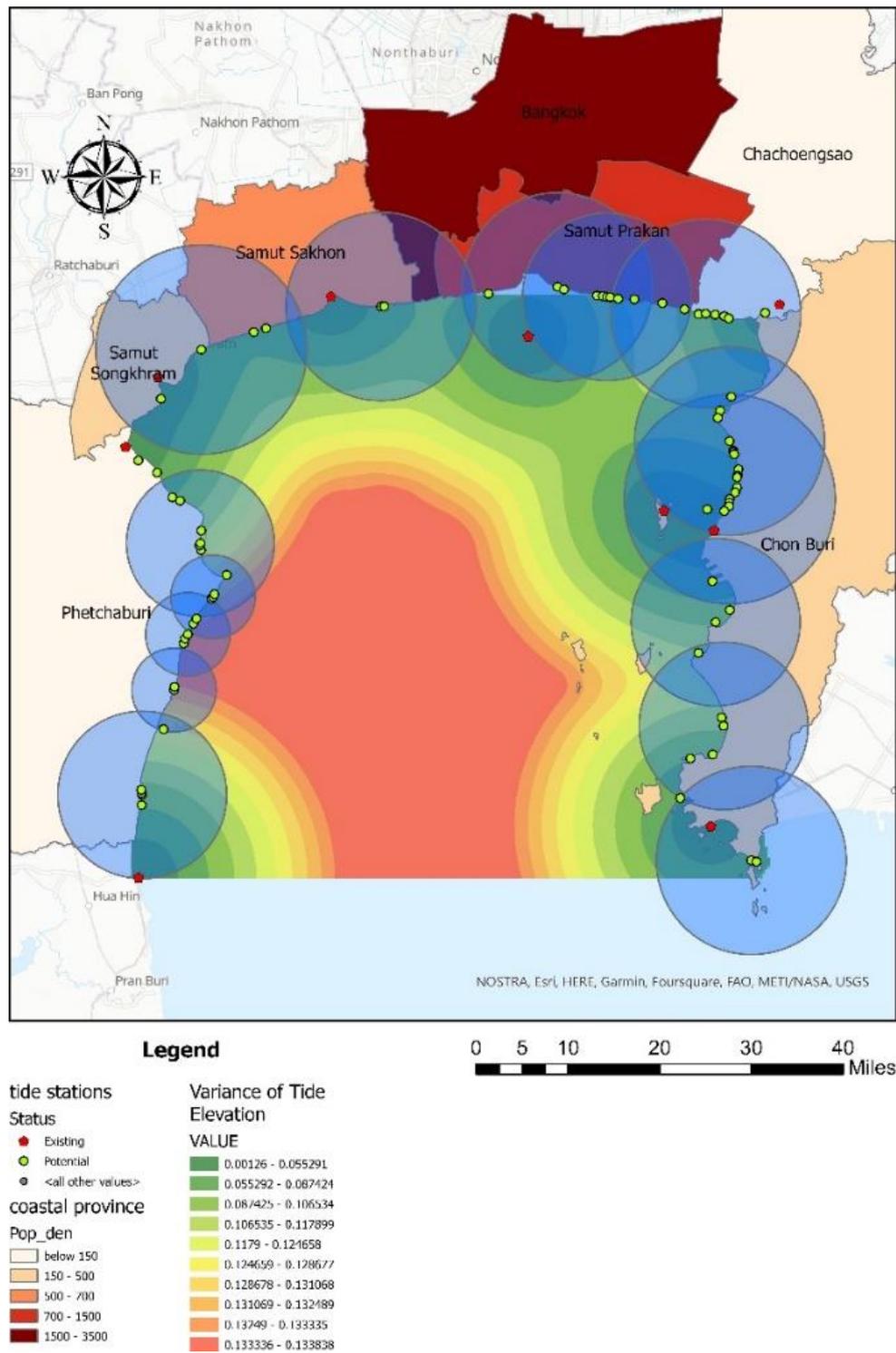


Figure 7 Result from P – median, P = 15, Weight, No Forcing Existing Tide Stations [5]

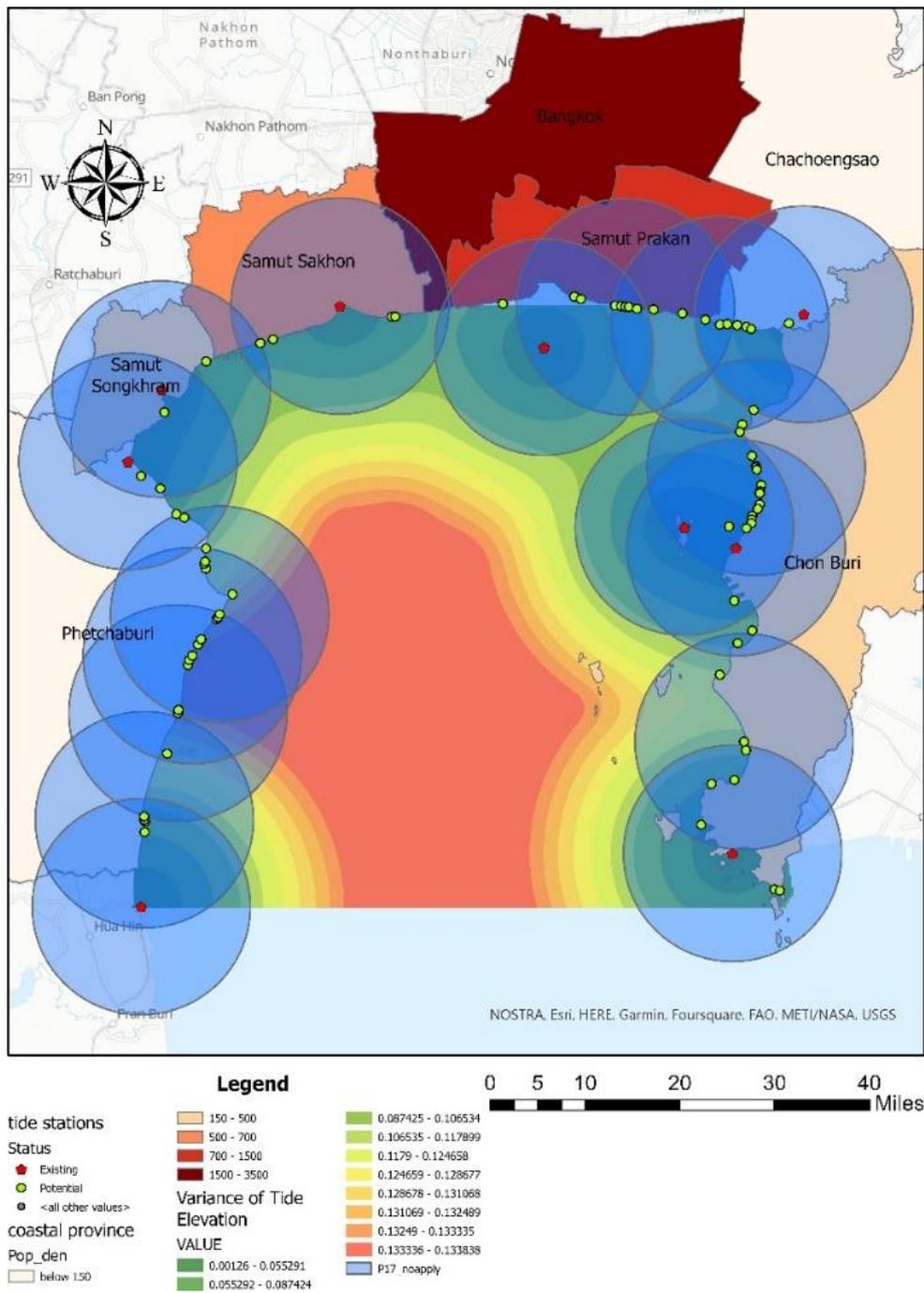


Figure 8 Result from P - median, p = 17, Weight, Forcing Existing Tide Stations, Same Radius [5]

**Table 3** The Estimate of Accumulative Costs of Tide Station

Conditions	Total Stations	Year				
		1 (USD)	2 (USD)	3 (USD)	4 (USD)	5 (USD)
Keep 9 existing stations	17	286,000	524,000	762,000	1,000,000	1,238,000
Re-arrange	15	300,000	510,000	720,000	930,000	1,140,000

From table 3, it is obvious that although the rearrangement condition requires a higher budget than keeping 9 existing stations at the beginning, in the 2<sup>nd</sup> year, the condition to keep 9 existing station condition begins to need more budget because the operating cost is greater than construction cost around 2 times. Therefore, this illustrates that rearranging tide stations in the study area with 15 tide stations is the most optimal solution in both spatial coverage and financial aspect terms.

## 6. Conclusion

The Historic Bay of Thailand is one of the important marine regions in Thailand, so mariners as well as people who live surround these areas required adequate and accurate tide information for many activities such as navigation in the water, tourist activities, fishery, and hydrographic survey. Although there are 9 existing tide stations in this area, they cannot cover all shorelines based on the standard of hydrographic survey. Consequently, large regions are left without the coverage of accurate tide information services.

With the advancement of location-allocation models and geographic information system (GIS), the P – median models can be implemented to analyze how to arrange tide stations in this study area to cover all shorelines effectively. The results demonstrated that P – median with weight as equation (6) and forcing 9 existing tide stations requires a greater number of tide stations than P – median with weight as equation (6) but not forcing existing tide station with 17 and 15 stations, respectively. Both results can cover all shorelines and emphasize more tide stations in areas that have high variation of tide elevation, greater population density, and a greater number of port numbers. Hence, P – median is also proper for locate tide stations to cover all demands. Additionally, after considering the financial aspect with construction and operating costs, P-median with weight as equation (6), but not forcing existing tide stations requires less budget after the second year of operating with only 15 tide stations in the system, so it is an optimal solution.

Nevertheless, there are some limitations in this study. Firstly, since there is no available data regarding potential locations for setting up tide stations, this information was obtained from satellite images and nautical charts. However, conducting ground truth surveys would provide more accurate data to cross-check the security and relevant conditions of each candidate site. Secondly, having information on the construction and operating costs of tide stations in Thailand would be more effective, as these costs vary by region. Additionally, more factors could be incorporated into the suitability analysis, such as the number of ships, presence of tourist attractions, areas affected by tides, and important locations that rely on tide information. Furthermore, to capture all tidal constituents completely, each tide station must operate for at least 18.6 years. Therefore, the removal of existing tide stations must take this requirement into account. Lastly, population density is not the best indicator of marine activity, as regions with higher population density do not necessarily experience more marine traffic. The most suitable data would be the number of ships in each zone; however, this information is difficult to access due to security and privacy concerns, and it is also highly dynamic. Thus, using the number of ships instead of population density would provide a more accurate representation for future research.

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