OPTIMUM PLACEMENT OF EMERGENCY RESPONSE STATIONS FOR MARITIME ACCIDENTS IN THE MARMARA SEA

by

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ABSTRACT

OPTIMUM PLACEMENT OF EMERGENCY RESPONSE STATIONS FOR MARITIME ACCIDENTS IN THE MARMARA SEA

In order to minimize the environmental effect of oil spill caused by maritime accidents, cleanup work has to begin as soon as possible. For that reason, Emergency Response Stations (ERS) are planned to be located according to possible accident places. But exact coordinates of accidents cannot be known before they happen, optimum location of ERS will be chosen according to stochastic model that depends on probability theory. Parameters which are related with accident place and response time are taken into consideration at this model. Since maritime accidental oil spill will move with wind and current, total response time will be calculated by means of wind and current direction and magnitude probability. By means of all data ERS planned for Marmara Sea, are allocated to optimum locations.

ÖZET

MARMARA DENİZİ'NDE MEYDANA GELEBİLECEK PETROL KAZALARI İÇİN ACİL MÜDAHALE İSTASYONLARININ OPTİMUM KONUMLANDIRILMASI

Marmara Denizi'nde kaza sonucu denize dökülen petrolün çevreye verdiği zararı en aza indirebilmek için mümkün olan en kısa sürede temizlik çalışmalarına başlamak gerekmektedir. Bu amaçla, muhtemel kaza noktalarına yakın yerlere Acil Müdahale İstasyonları (AMİ) konumlandırılması planlanmaktadır. Ancak kazanın nerede olacağı önceden koordinat olarak bilinmediği için, AMİ'lerin optimum konumları olasılık teorisine dayalı rassal bir model ile hesaplanmıştır. Bu model kaza yerinin ve müdahale süresini etkileyen diğer parametrelerin olasılık dağılımlarını esas almaktadır. Kaza sırasında denize dökülen petrol rüzgar ve akıntının etkisiyle hareket edeceği için, toplam müdahale süresi rüzgar ve akıntının yön ve şiddet olasılıkları kullanılarak hesaplanmaktadır. Bütün bu veriler aracılığı ile Marmara Denizi için planlanan AMİ'lerin optimum konumları hesaplanmıştır.

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LIST OF SYMBOLS / ABBREVIATIONS

A	smaller or equal to constrain solution matrix
Aeq	equality constrain matrix
As	area of sea
b	smaller or equal to constrain solution vector
beq	equality constrain solution vector
c(i,l)	current vector in l^{th} condition at i^{th} cell
d	travel distance
E[ ]	expected value
f(,)	joint probability density function d and v_s
g(,)	joint probability density function T_1 and T_2
$h_1()$	inverse function for d
$h_2()$	inverse function for v_s
i	cell indicator
j	potential ERS indicator
k^l	condition probability
l	condition indicator
m	number of cells
n	number of possible ERS
nc	number of cell
ns	number of stations
nt	number of situations
p(i,l)	movement vector of petroleum in i^{th} grid at l^{th} condition
p_i	accident probability of i^{th} cell
p_0	accident probability
ps	perimeter of sea
R	radius of circle
r_i	accident risk of i^{th} cell
T	weighted arrival time vector
T_0	weighted arrival time matrix

T_1	travel time to accident location
T_2	travel time to center of oil spill
T_g	arrival time for all conditions matrix
T_t	total arrival time
t_r	run time
v_b	boat speed
v(i)	i^{th} cell
v_s	velocity of oil spill propagation
w(i,l)	wind vector in l^{th} condition at i^{th} cell
x	decision vector
x(j)	j^{th} potential station
x1	x coordinate of 1^{st} node
x2	x coordinate of 2^{nd} node
y(j)	facility location indicator
y1	y coordinate of 1^{st} node
y2	y coordinate of 2^{nd} node
Δl	distance between nodes
ERS	emergency response station
ERS(j)	j^{th} emergency response staion
ERT	emergency response team

1. INTRODUCTION

In 2007, Turkish Undersecretary for Maritime Affairs started a feasibility study to determine the state of the art in the emergency response activities in the Turkish waters. Project was developed by The Scientific and Technological Council of Turkey (TUBİTAK). It consists of collecting maritime activity data, predict future problems and find solutions to predicted problems. A part of the project was about maritime accidents. First maritime accident data was collected which are later used for predictions. One of the predictions was accidents with damage.

Accidents with damage can be seen very often. If there is damage at the oil tank of the ship, spilling of oil is inevitable. Since ships are getting bigger, oil tanks are getting bigger which can eventually cause an environmental disaster. Thus, oil leakage has to be cleaned up as soon as possible.

There are some active and passive precautions. Vehicle Tracking System using radar is one an active precaution. Passive precautions can be listed as double layer oil tanks, oil spill response centers and so on. Controlling the entire maritime traffic and preventing all accidents is unrealistic. On the other hand checking every ship inside the territorial waters is not feasible. Therefore, an accident recovery system has to be constructed in order to minimize the effect of accidents.

1.1. Problem Definition

Subsequent to a maritime accident with petroleum leakage, oil spill cover the surface of the sea rapidly and effect the environment. By means of wind and current oil spill begins to travel at the water surface and after a while, oil slick begins to split out into smaller parts. Propagation and expansion of the spill make the response harder. Also oil left at the sea can move onshore and stick to the coastline, which is very hard to clean. All the listed causes mean that there is a reverse relation between response time and efficiency of cleanup.

Quick response to oil spill not only simplifies the cleanup process but also decrease the permanent effect of oil at the environment. Therefore, facilities which will respond to maritime accidents should be located at a minimum arrival time to incident scene.

For cleanup purposes Emergency Response Stations (ERS) can be established. These stations are designed for offshore cleanup processes and have the capacity to response every oil spill accident. Stations consist of qualified workers and a ship which contains booms, skimmers, absorbents etc. for mechanical cleanup of oil spill from the surface of the water.

ERS are planned to respond to oil spill only and not to save human life. Because, ERS ships are slow when compared to other rescue boats which can make the first action to save human life and secure the ship. But as a security check and for stopping oil spill, response ship will first move to accident location then move to oil spill center, even if the oil slick has moved away from the original accident point.

Location decision of ERS requires strategic planning. In other words, decision should be operative for the next 20-30 year. That means, location decisions will be taken before an accident and decision has to be supported with historical data and statistical analysis.

1.2. Objective of the Thesis

ERS should be located at optimum places to minimize arrival time to oil spill. Optimum locations will decrease response time for cleanup and reduce environmental effect of oil spill.

Aim of this thesis is to develop a methodology for locating ERS to optimum locations. Developed model can be used for any other sea; it will only need the data of the related sea. Probabilistic analysis will be done at the coming sections and according to results an optimization algorithm is tried to be developed.

In order to make the computations realistic, response time will be calculated until response ship reaches the moving oil spill and not the accident location.

1.3. Region Description

Marmara Sea is taken as the pilot region, for the application of the model. The main reasons for choosing Marmara Sea, are the high rate of maritime traffic, the fact that it is an enclosed sea and legally only one country has the authority, which is the Turkish Republic. Single authority makes response operations and their execution much simpler in the practice.

Marmara Sea’s boundary looks like an ellipse. There are two entrances to the sea, one of them is from South West direction and connects it to Aegean Sea and the other one is from North East Direction and connects it to the Black Sea. These entrances are called the straits of Çanakkale and İstanbul respectively.

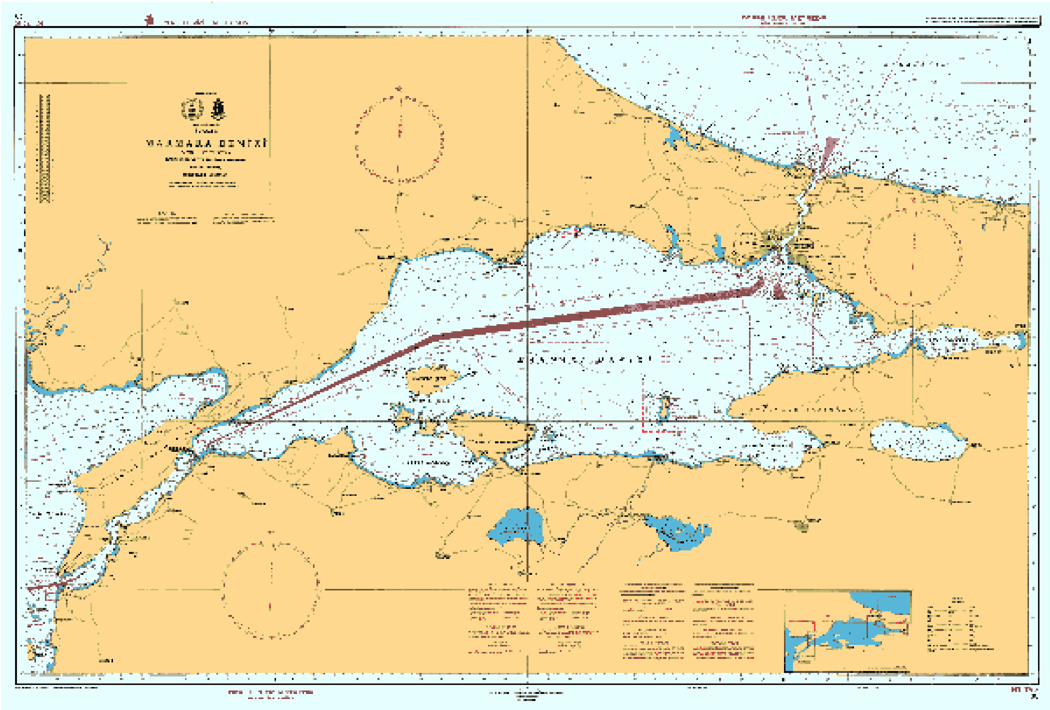


Figure 1.1. Map of Marmara Sea

In Figure 1.1. Marmara Sea Map is shown. If a ship is coming from the Black Sea to and going the Aegean Sea or vice versa, this ship has to pass through the Marmara Sea route is shown with red line in Figure 1.1. The Marmara Sea is smaller with respect to the Aegean Sea and the Black Sea. In addition to the transit maritime traffic Marmara Sea has a local traffic because of transportation of people and goods to industry sites. Therefore, its maritime traffic density is high.

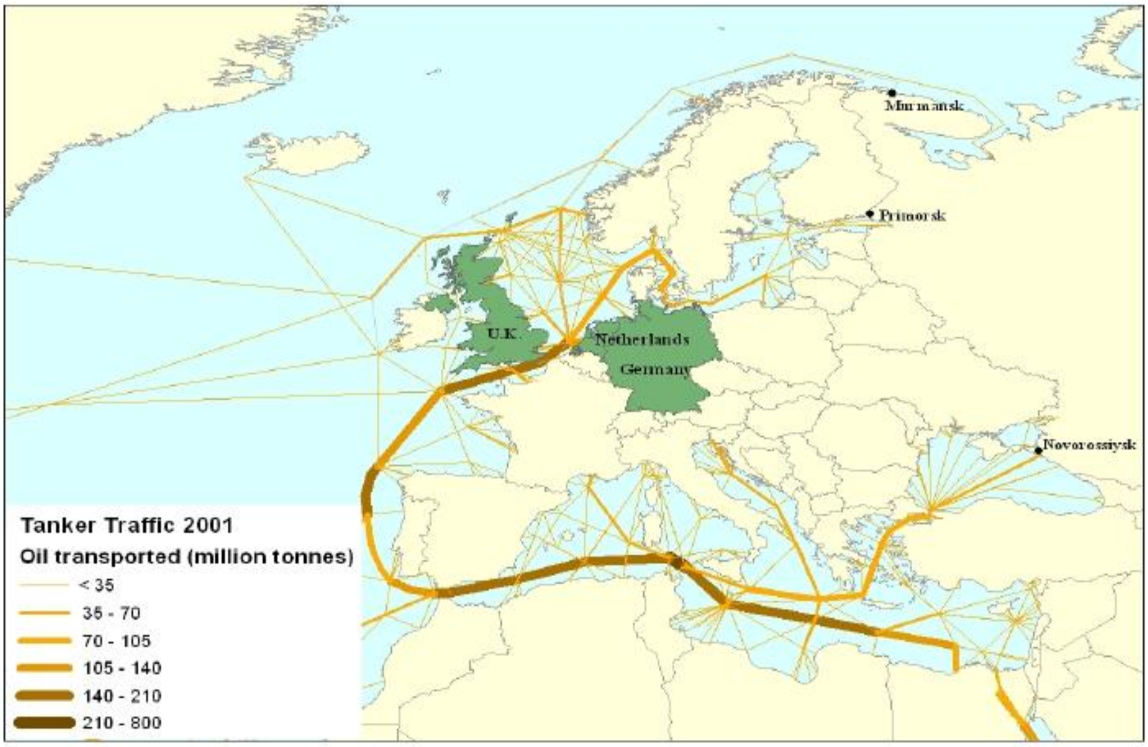


Figure 1.2. Map of Tanker Shipping Routes in Europe 2001 (Keisha Huijer, 2004)

In terms of oil transportation Marmara Sea has a critical place. In Figure 1.2. it is seen that 105-140 million tons of oil transported through Marmara Sea in 2001. (Keisha Huijer, 2004)

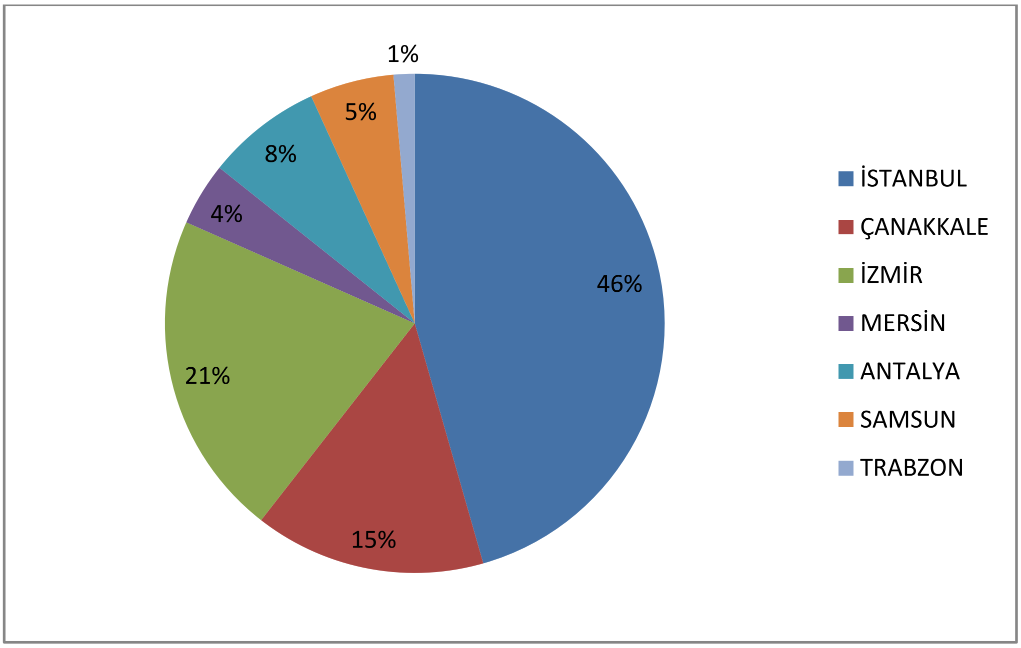


Figure 1.3. Percentage of Maritime Accidents according to regional directories in 2009 (Turkish Maritime Affairs website, 2010)

Another important parameter for Marmara Sea is the number of reported maritime accidents. In Figure 1.3. shows that, 46% of accidents are at İstanbul Region Directory and 15% of accidents are in Çanakkale Region. So 61% of all maritime accidents in Turkey are observed at Marmara region in 2009 according to Turkish Maritime Affairs Statistics.

2. LITERATURE REVIEW

2.1. Past Studies

The main purpose of this study is to locate ERS's at optimum places. Objective at decision is to minimize response time in given constrains. This topic is studied under location science. Hale& Moberg (2003) make a review of the topic. Examples of facility location models include, locating warehouses within a supply chain to minimize the average time to market, locating hazardous material sites to minimize exposure to the public, locating rail road stations to minimize the variability of delivery schedules, locating automatic teller machines to best serve the bank's customers, and locating a coastal search and rescue station to minimize the maximum response time to maritime accidents. There are two main objective functions in location science, one of them is minisum and the other is minimax. They are also called median and center problems respectively.

Mirchandani & Francis (1990) explains the difference between p-center and p-median problem: Open p facilities and assign each client to exactly one of them such that the maximum distance (unweighted case) or the maximum weighted distance from any open facility to any of the clients assigned to it is a minimum. These minimax objective functions are used for locational decision problems for emergency services.

2.1.1. The optimal number and sites of fire stations at Taipei's international airport.

Paper written by Tzeng & Chen, (1998) is a study of locating fire stations at an airport. According to study most of the airplane accidents happen before landing and after takeoff and usually people die because of explosion and fire after the accident. Therefore, location of fire stations must be planned specifically to decrease damage of airplane accidents.

In Tzeng, Chen (1998) study, the airport and its surrounding are divided into cells. Past accident locations are determined, and according to this data, accident probabilities of cells are found. Accident probabilities of cells are used to weigh the response time.

Afterwards, response time limit for decreasing accident loss is found. This time limit is put into model as constrain. Then setup cost and annual cost of locating a fire station is found. Also cost of response duration is calculated.

Objectives and constraints of the model are:

(i) Minimizing the total setup cost of fire stations and the cost of total loss in an accident. Loss caused by reacting inefficiently is defined as the total loss cost (TLC). Setup cost of fire stations is symbolized by "SC".

$$\min \min f_1 = \sum_i \sum_j s_{ij} \times SC + TLC \times e^{-\sum_i \sum_j s_{ij}} \quad (2.1)$$

where s_{ij} is the decision variable. If there is a fire station at ij s_{ij}=1, if not s_{ij}=0. They found the curves represented at Figure 2.1.

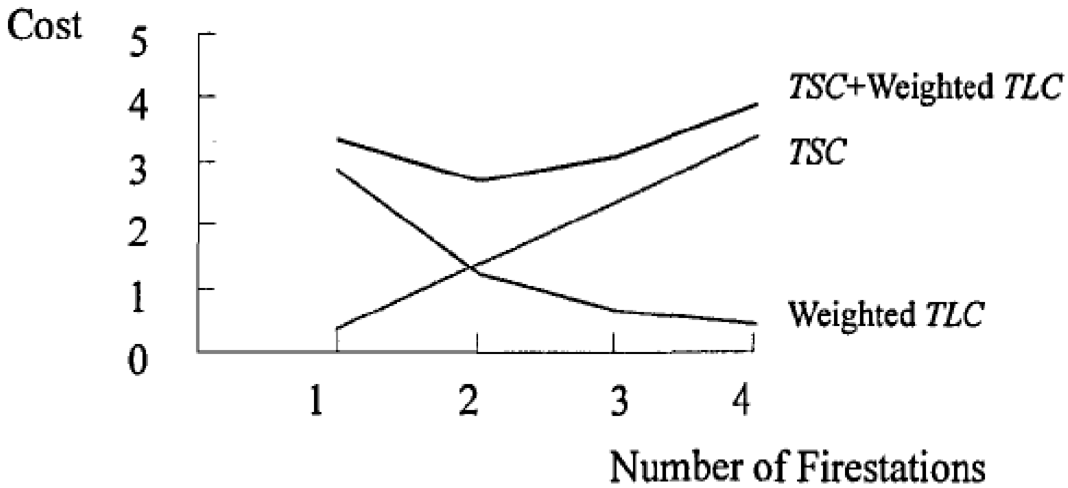


Figure 2.1. The trade-off between TSC and Weighted TLC (Tzeng&Chen, 1998)

(ii) Minimizing the longest distance from the fire station to any point at the airport. In order to increase the accessibility.

$$min\, f_2 = \sum_{\{(i,j)|s_{ij}=1, \forall i,j\}} \{max|x-i| + |y-i|\} \quad (2.2)$$

(iii) Minimizing the longest distance from any fire station to the high risk area.

$$min\, f_3 = max_{\{(i,j)|s_{ij}=1\}} \sum_i \sum_j r_{ij} \times \{|x-i| + |y-i|\} \quad (2.3)$$

r_{ij} is the risk rank, computed based on accident statistics for different areas at or near an airport.

Since the problem is a multi-objective type, objective functions are optimized by using fuzzy logic algorithm.

There are predetermined lower and upper bounds Results of functions (f_1, f_2, f_3) have. If the result of function is better than upper bound it gets 1, if the result is between upper and lower bound it gets a value between 1 and 0 and if the result is smaller than lower bound it gets 0. The locations satisfying maximum benefit will be the optimum places of the fire stations.

2.1.2. Optimal Response to Oil Spills: The Strategic Decision Case:

Psaraftis' (1984) paper deals with the strategic aspect of the oil spill response problem, which is with the problem of deciding where to locate adequate capability to respond to potential oil spills. Formulate a model for the strategic oil spill response problem, present some illustrative applications and discuss uses of the model within the existing or alternative policy and regulatory environments.

In Psaraftis' (1984) paper, the cost of oil spill per ton, spill rate of oil per hour, response time duration and management cost of facilities are used. They construct an objective function by using the input variables. Objective function summation of cost of opening new facilities, cost to acquire capability, expected cost to mobilize and transport equipment to the spill site, expected cost of cleanup, expected cost of damage due to unsatisfied demand and expected cost of damage due to delay and equipment.

Ceder (2000) worked on Psaraftis (1984) paper. The main difference is the solution method of the objective function. A synthesis algorithm is used for finding the solution of the objective function.

2.2. Definitions of Maritime Terms

Definitions of maritime terms listed below are taken from IMO's formal safety assesment document, 2002.

- Accident: An unintended event involving fatality, injury, ship loss or damage, other property loss or damage, or environmental damage.
- Accident category: A designation of accidents reported in statistical tables according to their nature, e.g. fire, collision, grounding, etc.
- Frequency: The number of accidents per unit time (e.g. per year)
- Hazard: A potential to threaten human life, health, property or the environment.
- Risk: The combination of frequency of accidents and the severity of the consequence.

3. METHODOLOGY

In this study, it is assumed that there is a maritime accident with oil spill over Marmara Sea and response stations will be located in order to recover spilled oil and decrease the environmental effect in minimum time.

Before starting the study, Marmara Sea map and its coastline drawing is needed. From USGS Coastline Extractor a 1/20.000 map is downloaded and used in this study. In Figure 3.1. coastline of Marmara Sea is given.

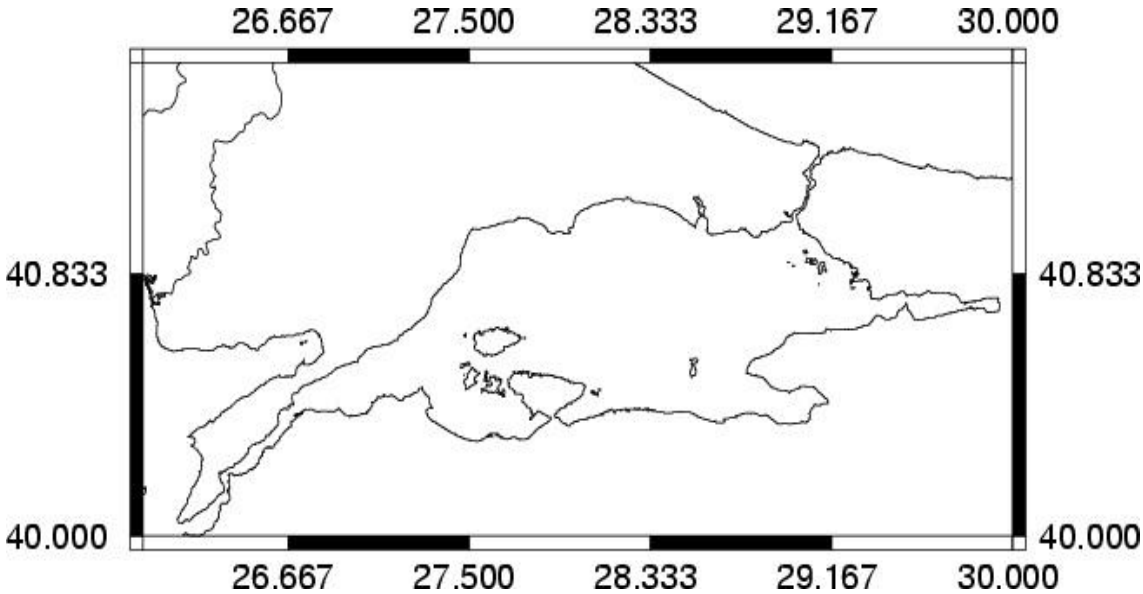


Figure 3.1. Marmara Sea Coastline map (USGS Coastline Extractor,2010)

Maritime accident coordinates are investigated from past accident reports. Accident coordinates are spots over the sea. Working with small spots will take too much time and effort. Therefore, Marmara Sea is divided into 10 km by 10 km cells in order to decrease working time. In Figure 3.2. center of cells are represented with blue circles.

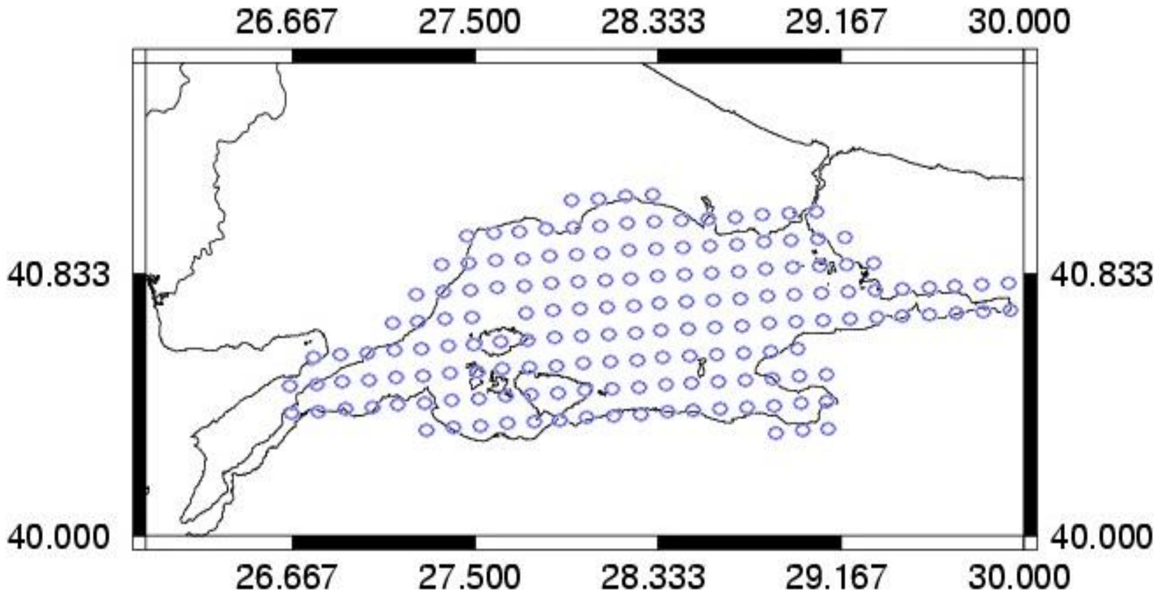


Figure 3.2. Center of 10km by 10km Grids over Marmara Sea

After dividing Marmara Sea into 10 km by 10 km cells, possible response locations have to be determined. Some of the cells contain land percentage in their boundaries. These cells are assumed as possible station locations and represented in Figure 3.3. with blue dots.

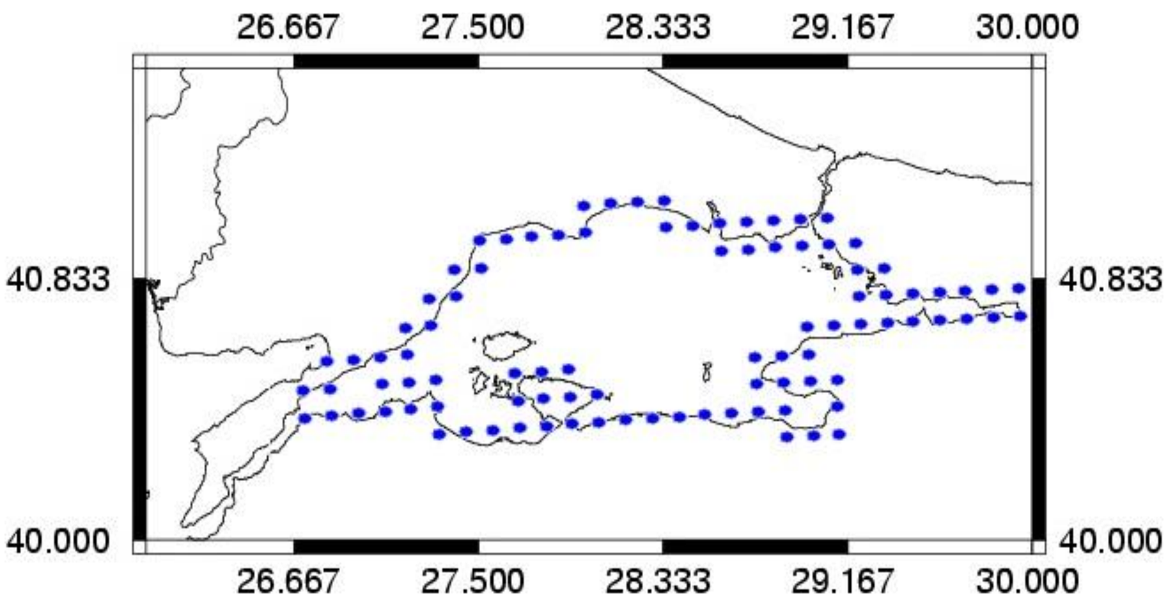


Figure 3.3. Possible Station Locations at Marmara Sea Boundary

In terms of accident probability or accident risk, some cells' are more important than others. Meaning that the important cells have to be recovered quicker than other cells. Therefore, a ratio has to be included in the calculations for weighing importance of cells. The ratios of cells are accident probability and accident risk and they are taken from TUBİTAK as a calculated data.

Accident probability of cells calculated and predicted for future, according to past maritime accident events. Then, impact of an accident in each cell is predicted based on the presence of sensitive areas (bird resting, nature preserve, economic or environmental zones). The relative rating is made by expert opinions. By means of accident probability and accident impact, accident risk of a cell is calculated.

According to model there is an oil spill danger after a maritime accident. Wind and current at the accident location will move oil spill on the surface of the sea. Motion of oil spill changes the response time. Thus, for a realistic time optimization, movement of oil spill is calculated for each condition and used in the optimization process.

Spilled oil can be cleaned-up mechanically or chemically. According to regulations in Turkey, only mechanical clean-up can be done. Mechanical clean-up is done by means of booms and skimmers during the offshore response. Boats are needed for transporting the booms and skimmers and placing them at sea. Therefore, calculation of arrival time depends on boat which is another parameter used at the model.

To sum up all the steps of a maritime accident; the start of cleanup process is ordered when a maritime accident occurs and oil spill begins, emergency response team (ERT) gets accident coordinates and begin to go to the accident location. As ERT travels towards accident location oil spill moves with wind and current. Then ERT arrives to accident location to check if there is a problem with the ship, and go to the oil spill center from the accident location. When ERT arrives to oil spill center clean-up process begins. In Figure 3.4. there is an illustration scheme for response stages to a possible oil spill accident.

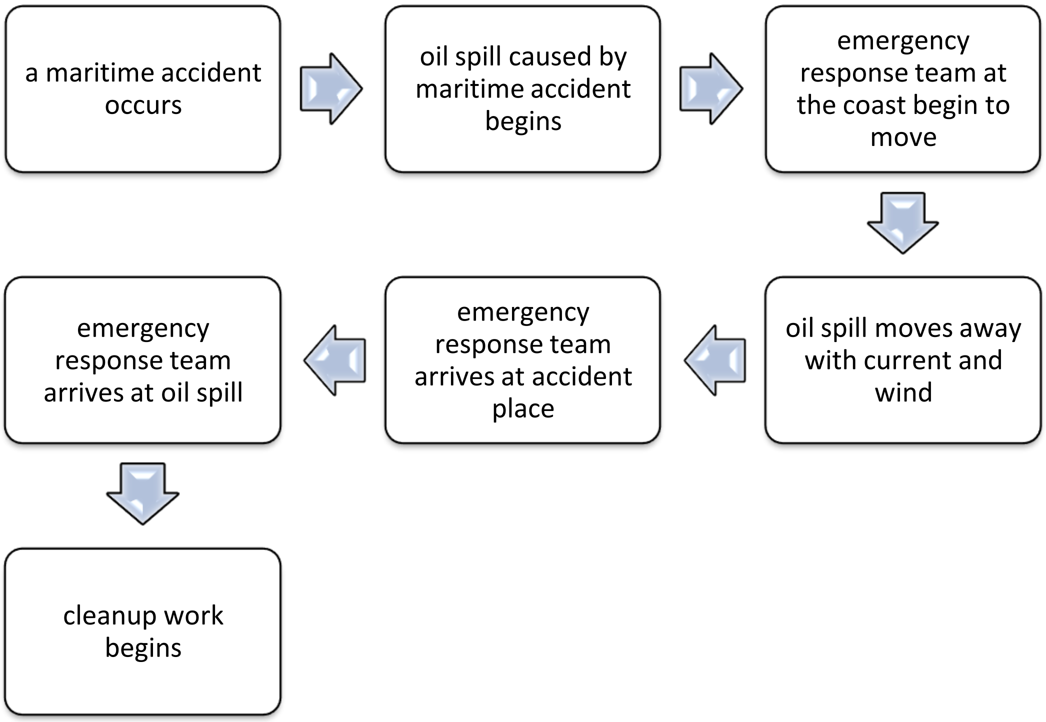


Figure 3.4. Accident response stages

According to accident scheme in Figure 3.4. an objective function is developed. Objective function at placement of the ERS is to minimize the maximum response time to oil spill. Response time is the combination of arrival time to accident location and the arrival time from accident location to oil spill center. Both of these time durations depend on cell's conditions. There will be ratios for importance of cells and frequency of weather conditions and they will be used for weighing the response time. Importance of cell is accident probability or accident risk and frequency of weather condition is the probability of wind and current.

4. SITE CONDITIONS

At this section of the thesis site specific conditions of Marmara Sea, and statistic data analysis are given. Also by means of data analysis, analytical solutions for imaginary conditions is tried to be developed.

4.1. Wind

One of the factors that causes oil spill to move is the wind. Long term wind records are used to predict the speed and direction of wind. So at the calculation predictions can be used.

Wind data is taken from Istanbul Florya and its duration is from 1995 to 2001. Data is the daily average of magnitude and direction. Magnitude distribution of wind is given at Figure 4.1.

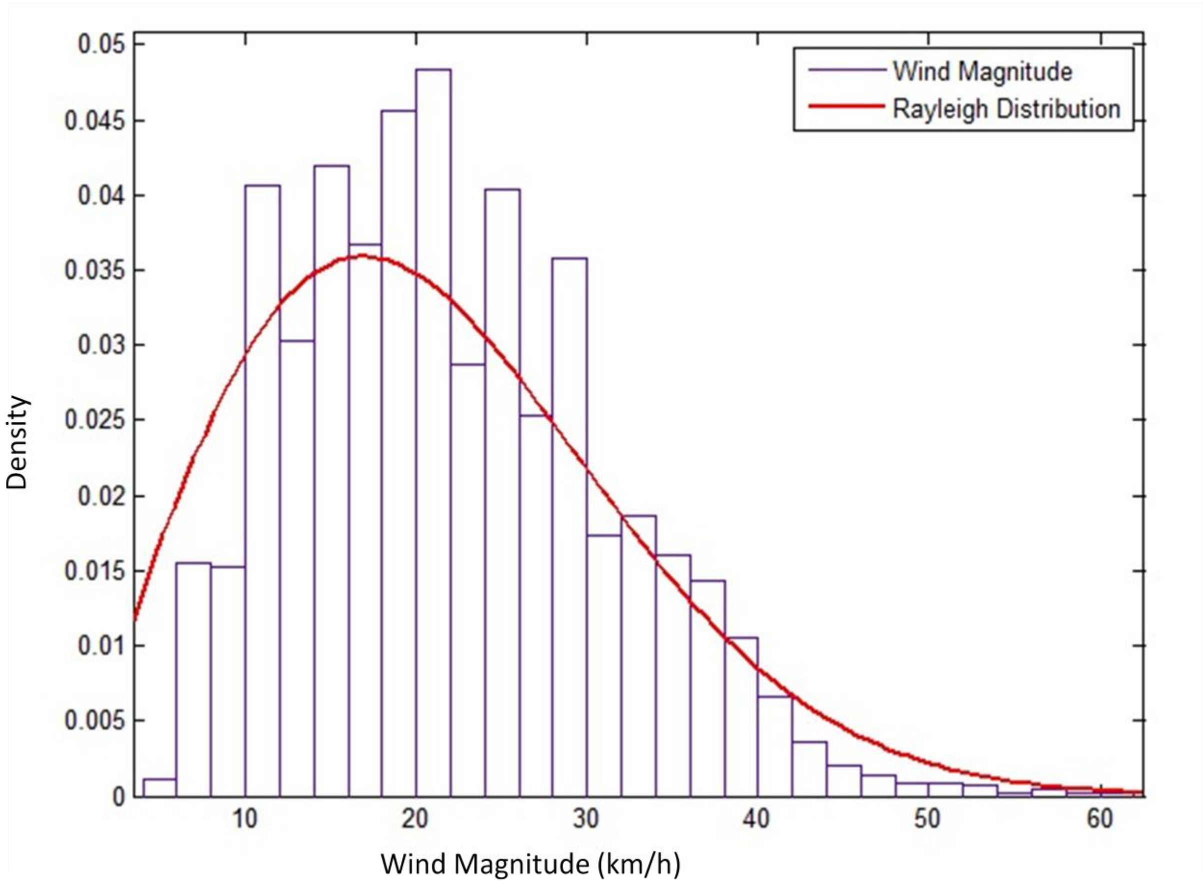


Figure 4.1. Probability Density Function of Wind Magnitude

In Figure 4.1. probability mass function of recorded wind magnitude is plotted. Then most suitable probability density function is found as Rayleigh distribution. Also most expected wind magnitude is found as 20km/h (10.8 knots).

Also directions of wind data are studied. Its directional probability distribution is observed and given as a wind rose diagram in Figure 4.2.

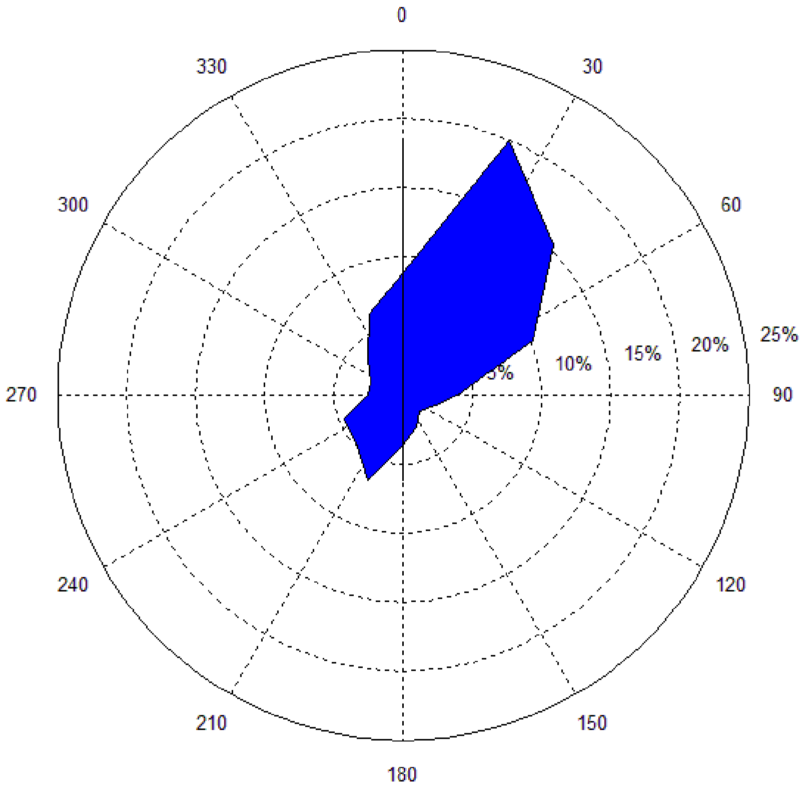


Figure 4.2. Wind Rose in the Marmara Sea (blowing from)

In Figure 4.2. it is observed that most probable wind direction is NNE with 20% percent.

4.2. Current

Another factor that effects the movement of oil spill is current. Current data is taken from TUBİTAK. Data consist of 12 month average magnitude and direction of each month. Average current magnitude and direction for each cell represented Figure 4.3.

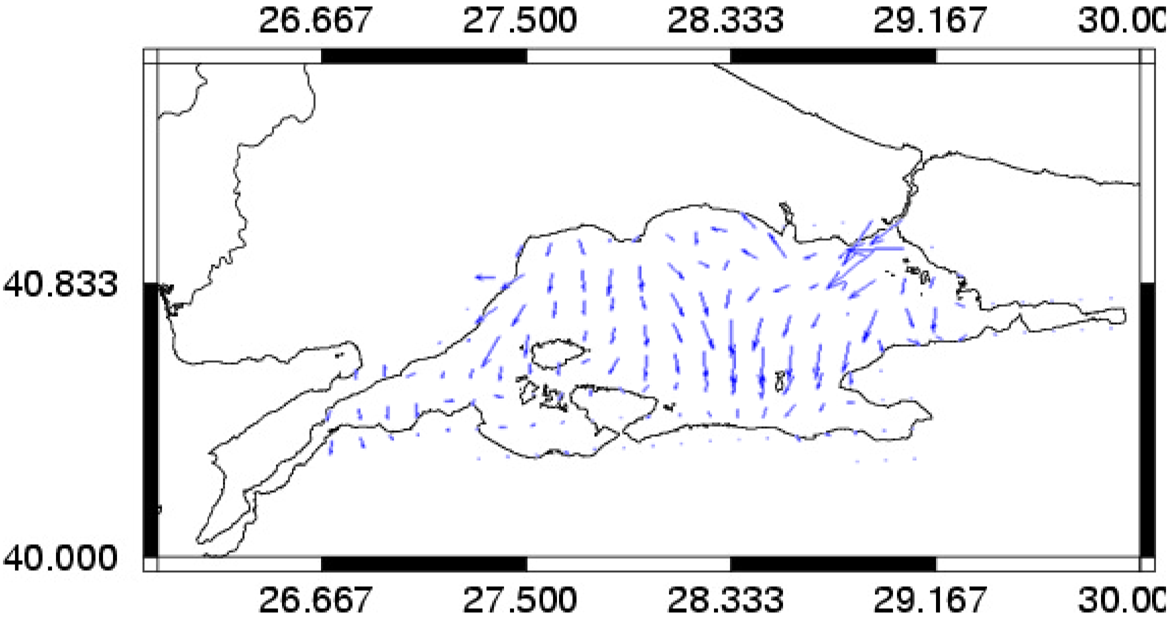


Figure 4.3. Marmara Sea Current Map

The probability density function of expected current magnitude over Marmara Sea is given at Figure 4.4.

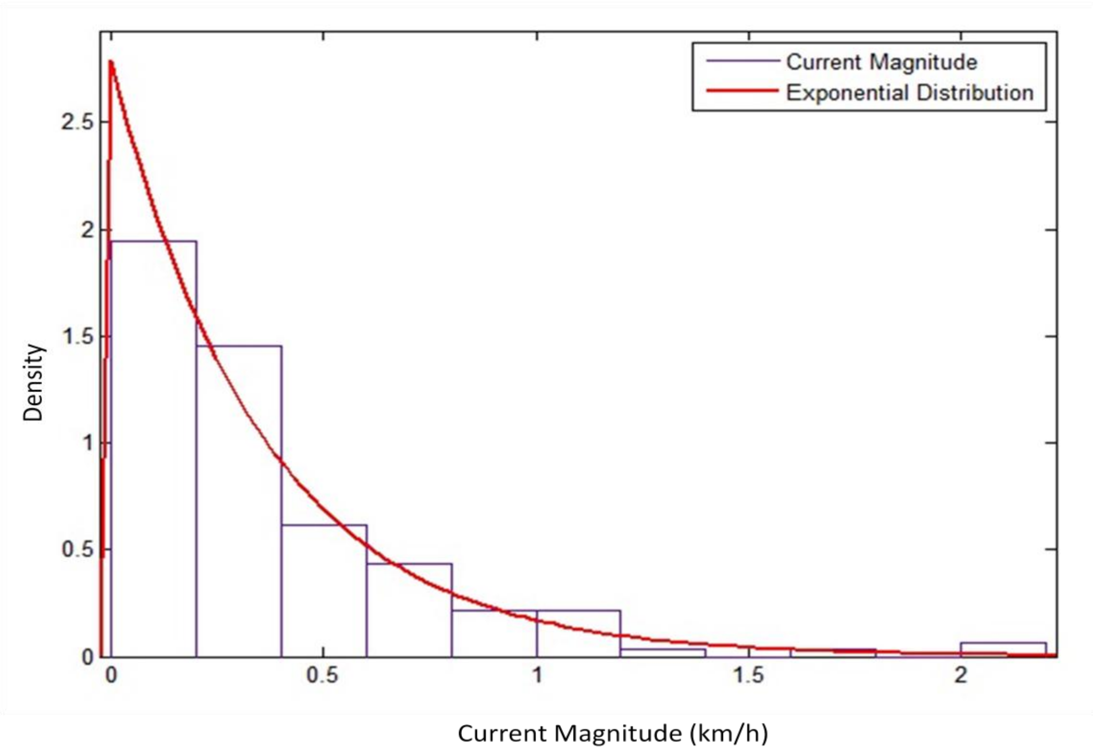


Figure 4.4. Probability Density Function of Current Magnitude

For finding probability distribution function of current magnitude, first probability mass function is plotted from which the most suitable probability distribution function is found as the exponential distribution.

Current directions of each cell for 12 months are observed and presented in Figure 4.5. as going to directions.

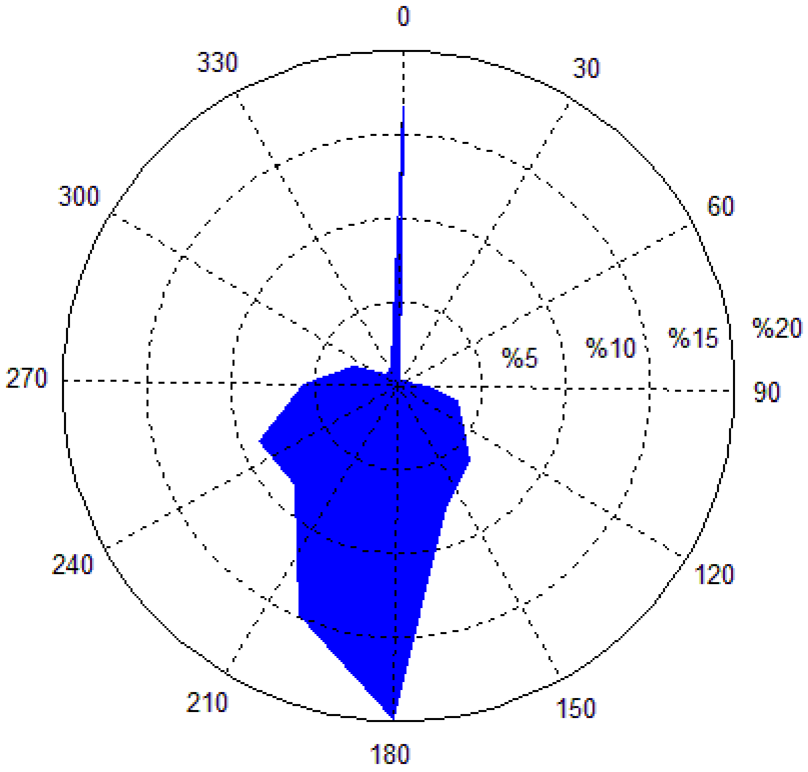


Figure 4.5. Current Direction Probability (going to)

4.3. Oil Spill

According to IMO (International Maritime Organization) 100% percent of current drifts oil spill at water (1.5 km/h current moves the oil slick 1.5km/h in the direction of current.). Therefore, current is the most effective parameter for predicting the slick movement. Marmara Sea current map is given at Figure 4.3. Directional changes and variation of the magnitude of current is very small throughout a year. Thus, average values are used for current data.

Another factor that effects the movement of oil spill is wind. Wind sweeps the slick as 3% percent. (30km/h wind drifts the oil spill 0.9km/h in the direction of the wind.). Wind is not as effective as current, but it is effective if the magnitude of the current is small.

In order to show the effect of wind with current, two dominant wind directions (NNE wind & SSW wind) scenarios are represented at the following sections of the thesis.

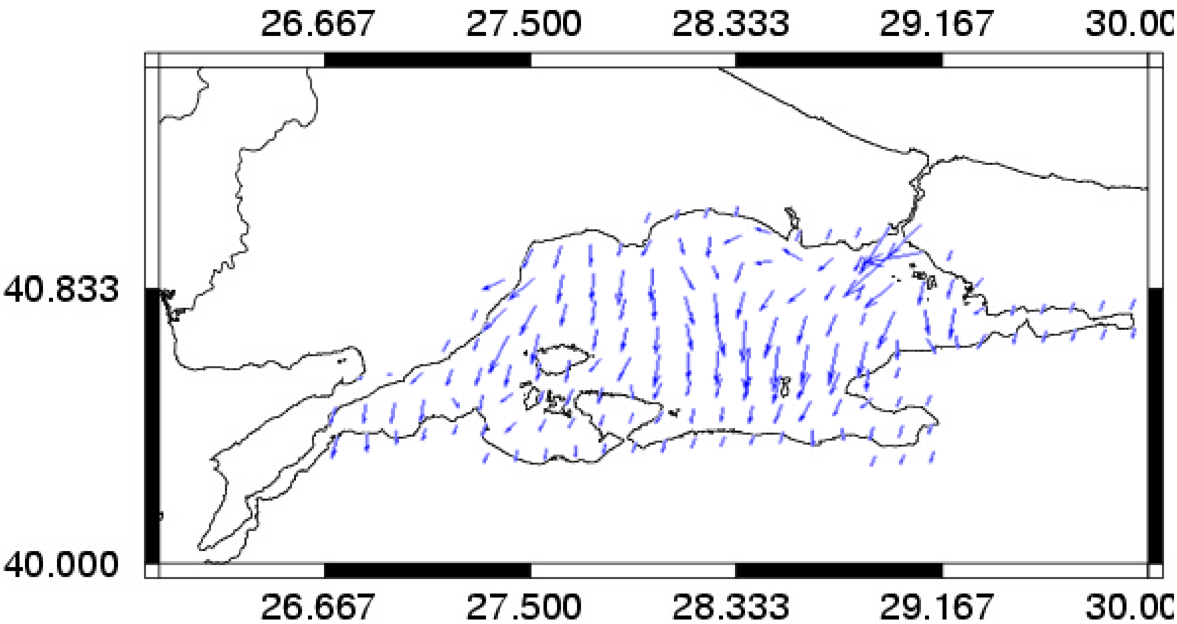


Figure 4.6. Oil spill movement vector for NNE wind and average current

Model output for oil spill movement vector at NNE wind and expected current condition are given in Figure 4.6. When Figure 4.6. is compared with the current map (Figure 4.3.), little difference is observed at the sections where the current is strong, whereas wind becomes effective where current is weak.

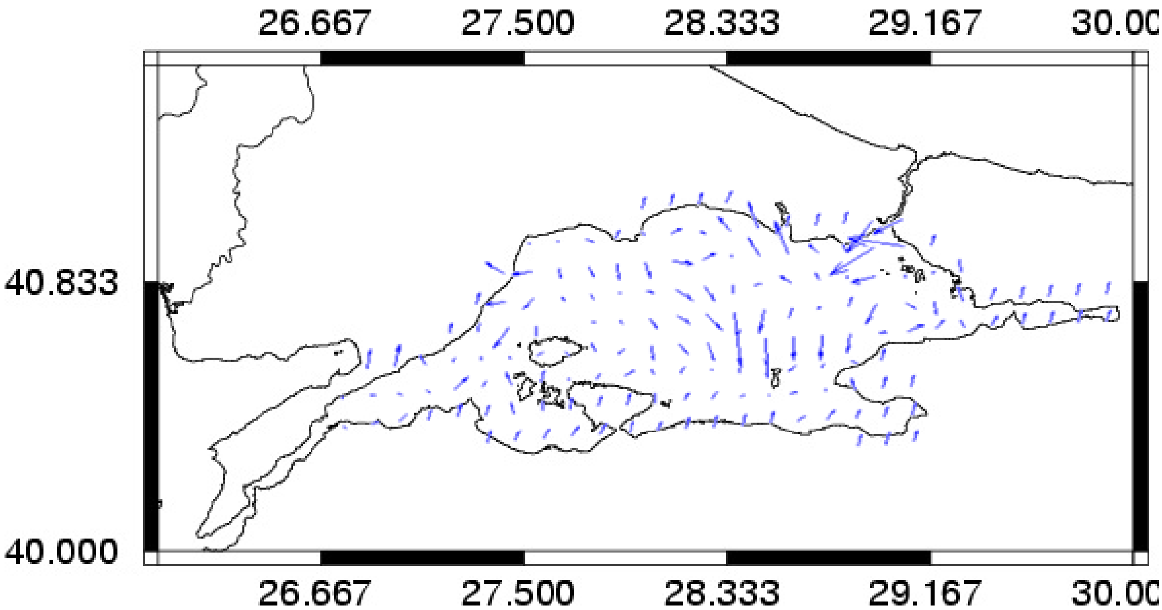


Figure 4.7. Oil spill movement vector for SSW wind and average current

From Figure 4.7. it is observed that, SSW wind changes the direction of the oil spill movement where magnitude of the current is small, and it slows down oil spill at strong current regions.

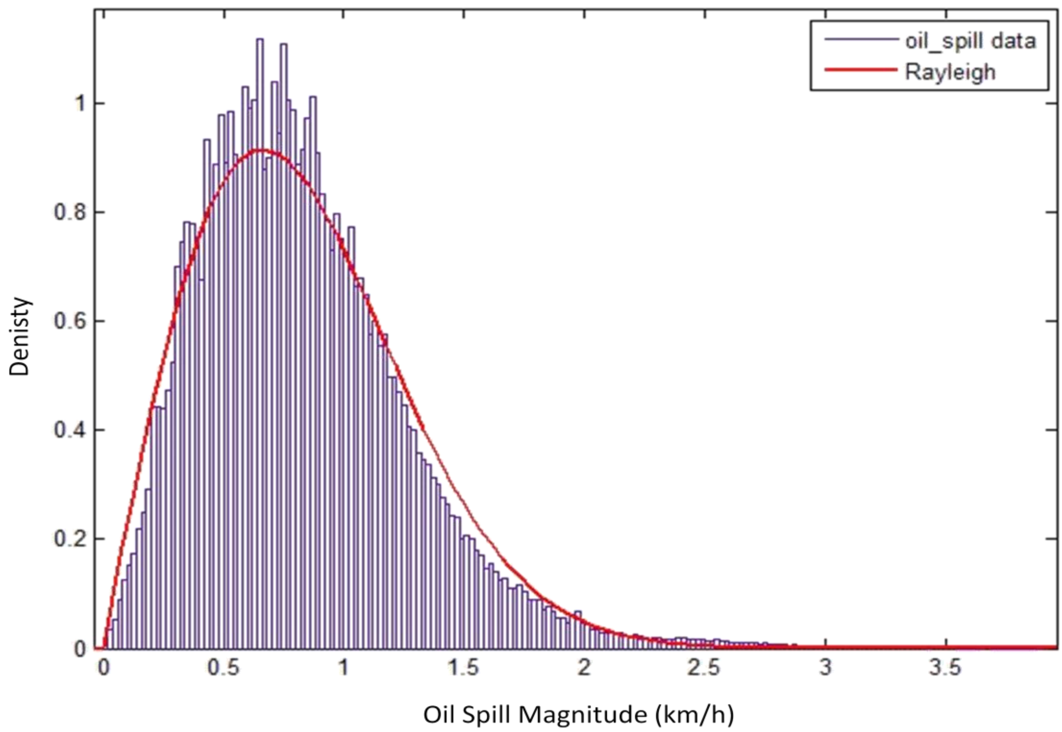


Figure 4.8. Oil Spill Propagation Speed Distribution

Oil spill movement speed distribution is plotted in Figure 4.8. By using Matlab Fitting Toolbox most suitable distribution is found as Rayleigh distribution. Rayleigh Distribution function is given in Equation (4.1).

$$f(v_s) = \frac{v_s}{\sigma^2} e^{\left(\frac{-v_s^2}{2\sigma^2}\right)} \tag{4.1}$$

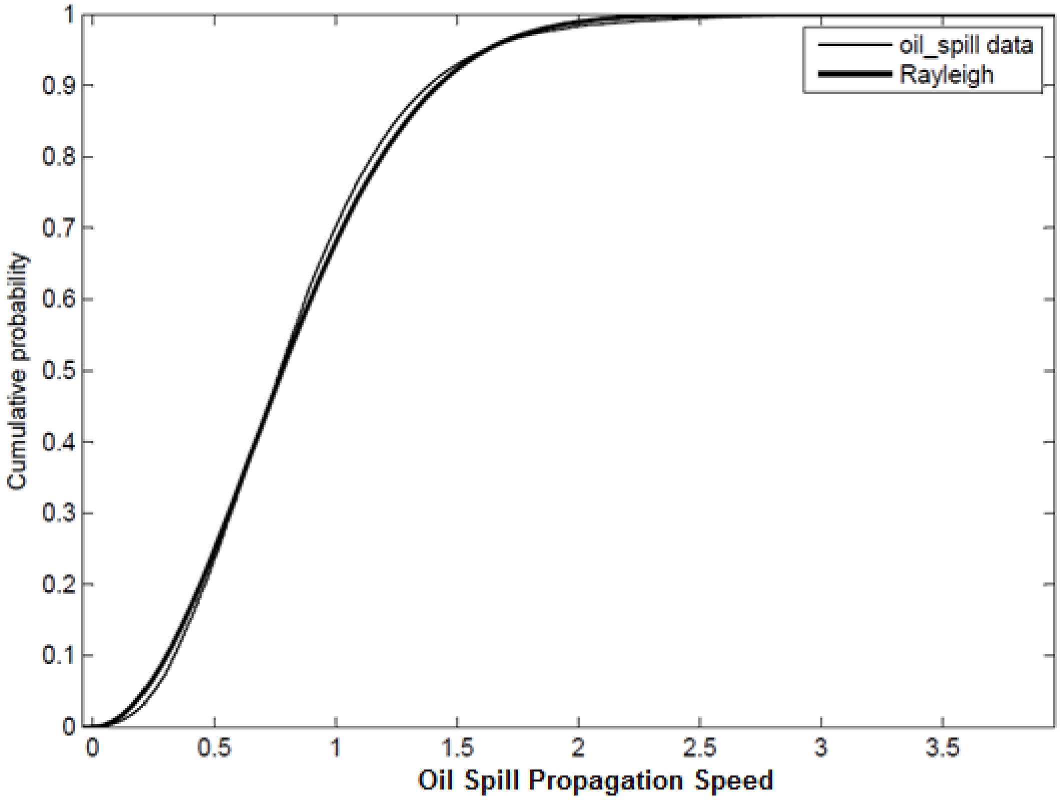


Figure 4.9. Oil Spill Propagation Speed Distribution vs Rayleigh Cumulative Distribution

In Figure 4.9. Oil Spill Propagation Speed Distribution is compared with Rayleigh Cumulative Distribution. Small difference between distributions is observed in Figure 4.9.

According to Matlab Fitting Toolbox analysis “b” value is found as 0.663114, expected value of v_s is found as 0.831091 and variance of the fitted function is found as 0.18873.

In Table 4.1. results of fitted Rayleigh distribution for associated v_s are given.

Table 4.1. Values for associated v_s

v_s	Rayleigh
	$f(v_s)$
0	0
0.39	0.746064
0.78	0.8881198
1.17	0.5610547
1.56	0.2229273
1.95	0.0587584
2.34	0.0105202
2.73	0.0012957
3.12	0.0001106
3.51	6.58E-06
3.9	2.73E-07

4.4. Maritime Accident Types

Maritime accidents are classified according to their types as grounding/ramming, collision, fire/explosion, sinking/failure. According to accident data for Marmara Sea, type percentages are given in Figure 4.10.

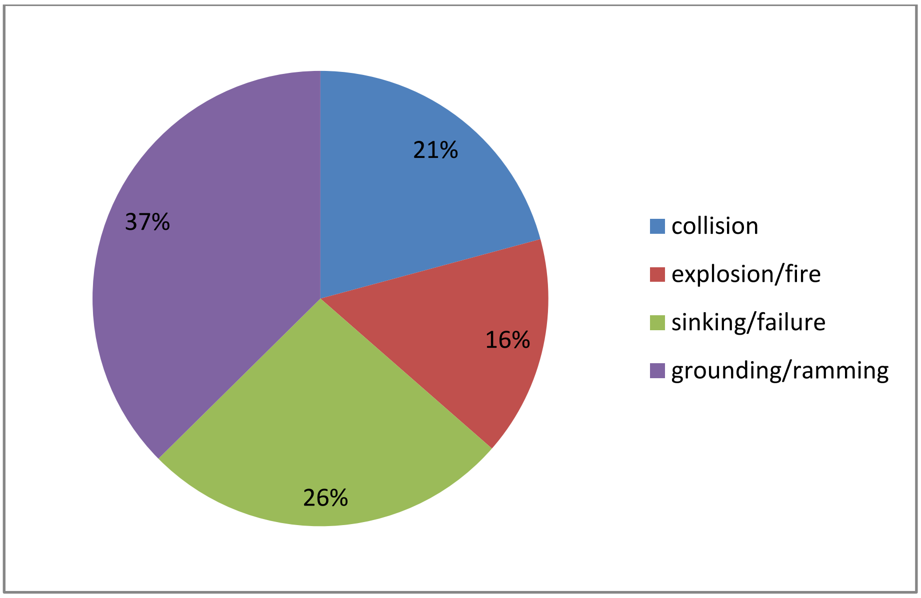


Figure 4.10. Accident type percentages in Marmara Sea (Turkish Maritime Affairs website,2009)

Most common maritime accident in Marmara Sea is grounding/ramming then sinking/failure. These accident types caused most of the oil spill events.

4.5. Accident Probability

Past maritime accidents are studied by TUBİTAK (2007) and coordinates are recorded. Then according to recorded data, accident probability values of cells over Marmara Sea are distributed. Accident probability distribution of Marmara Sea is given in Figure 4.11.

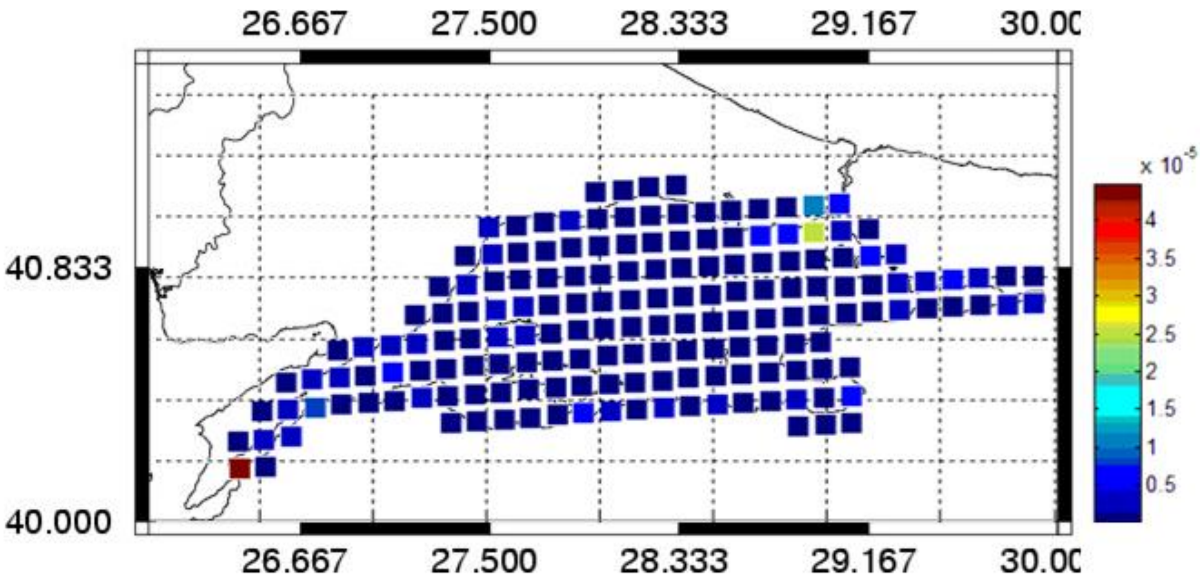


Figure 4.11. Marmara Sea Accident Probability Distribution Map

In Figure 4.11. sum of the accident probability of all cells is 1. That means it is assumed that there is an accident at Marmara Sea region. Color scale at the right side of the figure, represents the scale of accident probability. It is seen that accidents at the entrance of the straits increases probability and also at Gulf of İzmit accident probability is higher than the mean of the Marmara Sea.

4.6. Accident Impact and Sensitivity Distribution

Accident impact is the effect of a possible maritime accident in the cells. It is assumed that there is a maritime accident at each cell. Then environmental impact of an accident is graded for every cell of Marmara Sea. Accident grade is given according to environmental Grade of impact is given at Figure 4.12.

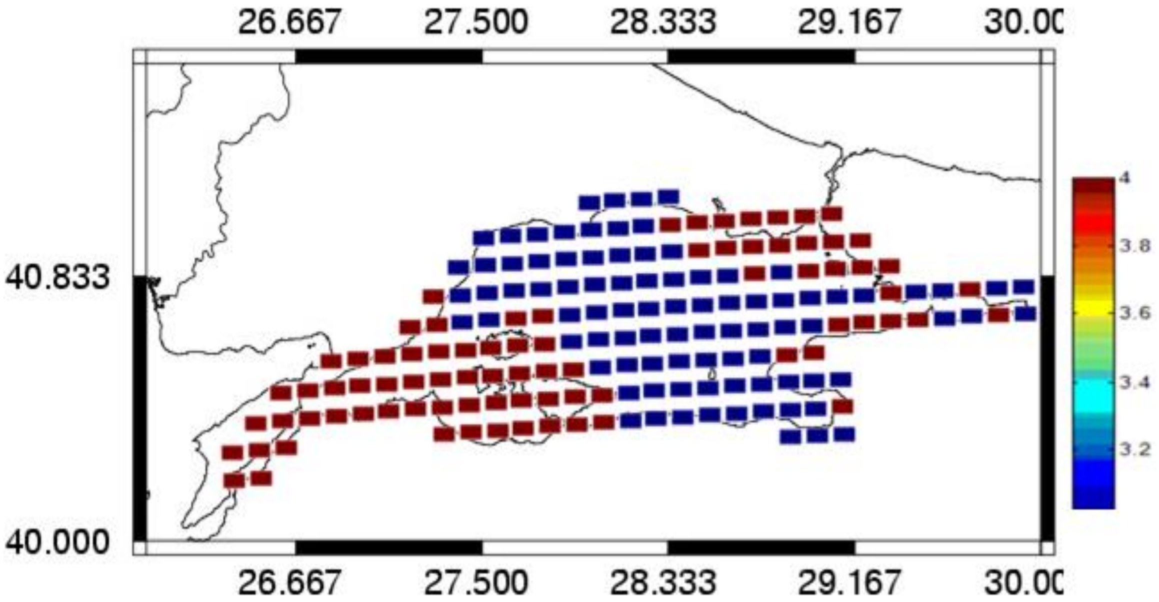


Figure 4.12. Marmara Sea Accident Impact Map

Environmental effect of maritime accident increases at the entrance of the straits and Western part of the Marmara Sea.

4.7. Accident Risk

After finding the accident probability and accident sensitivity values of a cell, accident impact is calculated for grading risk of a cell. It is a combination of accident probability and accident sensitivity. Values for Marmara Sea are given in Figure 4.13.

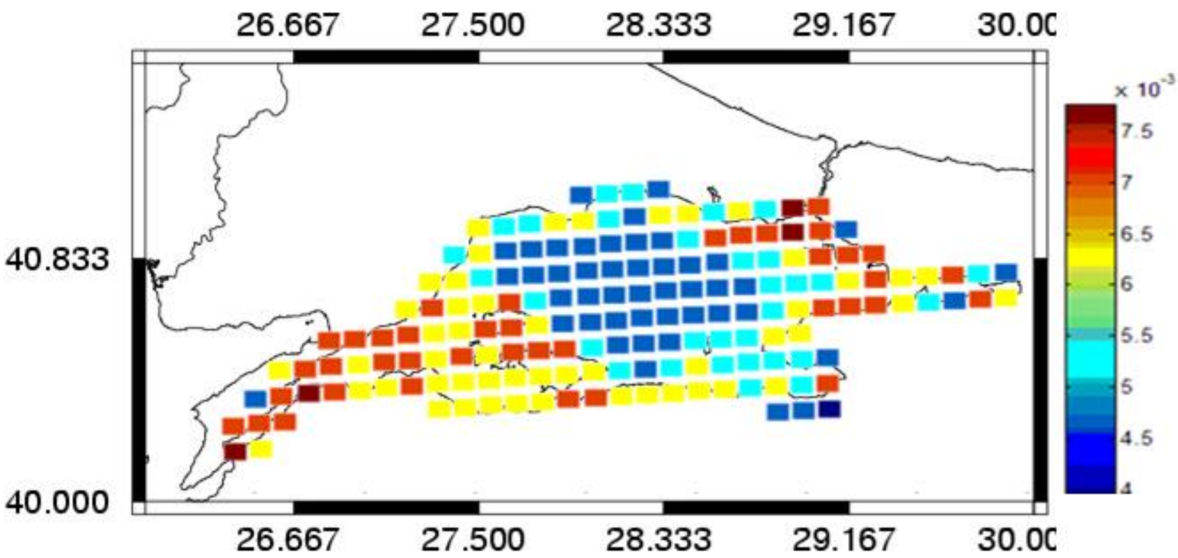


Figure 4.13. Marmara Sea Accident Risk Map

Since accident risk is combination of accident probability and impact sensitivity, the entrances of the Straits have highest accident risk. Lowest risk is observed in the middle cells of the Marmara Sea.

4.8. Analytical Solution Trials

In this section imaginary seas are created and also perfect conditions are assumed for wind, current , accident place and ERS locations.

4.8.1. Circular Sea

4.8.1.1. Case 1: There is a sea with a perfect circle boundary. Maritime traffic is going on at the sea. Probability of having an accident at the sea is uniformly distributed, with probability of p_0. At the center of the circle there is an emergency response station for decreasing the environmental effects of the accident. It is important to find the expected travel distance of the response boat (E[r]).

If it is given that there is an accident inside the boundary of circle and having an accident per unit area is $p_0/\pi R^2$, where R is the radius of the circle. Let's take infinitesimally small area called dA.

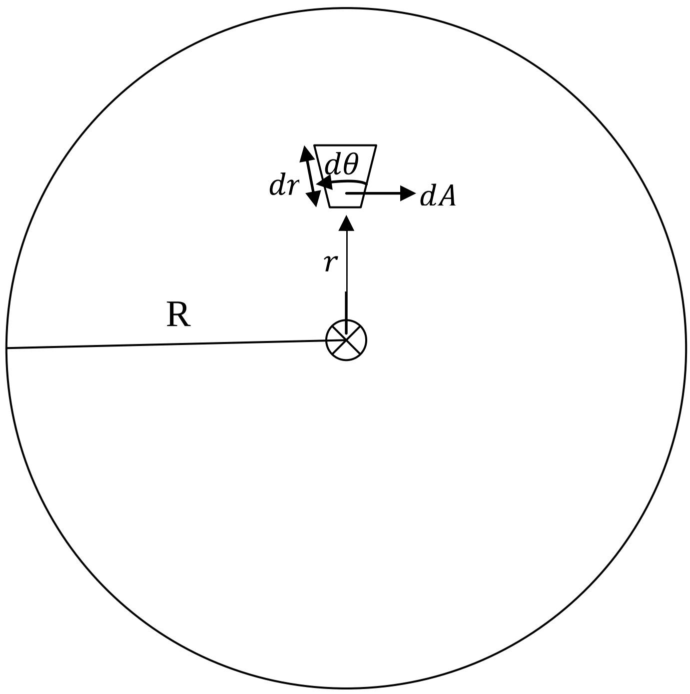


Figure 4.14. Circular Sea Representation

r is directly related with the accident place. Therefore, accident probability of the spot is also the probability of the value of r.

$f(x) = probability\ density\ function$

$$f(r,\theta) = \frac{p_0}{\pi R^2} \tag{4.2}$$

where,

f(r,Θ)≅ accident probability density function

p_o≅ probability of having an accident inside the circle

$$dA = r \times dr \times d\theta \cong infinitesimally \quad small \quad area \tag{4.3}$$

$$\int_0^R \int_0^{2\pi} r \times \frac{p_0}{\pi R^2} \times dA = \int_0^R \int_0^{2\pi} r \times \frac{p_0}{\pi R^2} \times r \times dr \times d\theta = E[r] \tag{4.4}$$

Since it is known, there is an accident $p_0 = 1$ and

$$\int_0^R \int_0^{2\pi} r \times \frac{1}{\pi R^2} \times r \times dr \times d\theta = \int_0^R r \times \frac{1}{\pi R^2} \times r \times 2\pi \times dr = \frac{2}{3} R^3 \frac{1}{R^2} = \frac{2}{3} R = E[r] \tag{4.5}$$

4.8.2. Elliptical Sea

Assume that there is an elliptical sea and a maritime accident occurs at the center of it. An oil spill occurs after the accident. Oil spill is moving with current and wind and its velocity vector is called v_s. Magnitude of v_s is a random variable which is a function of $f(v_s)$.

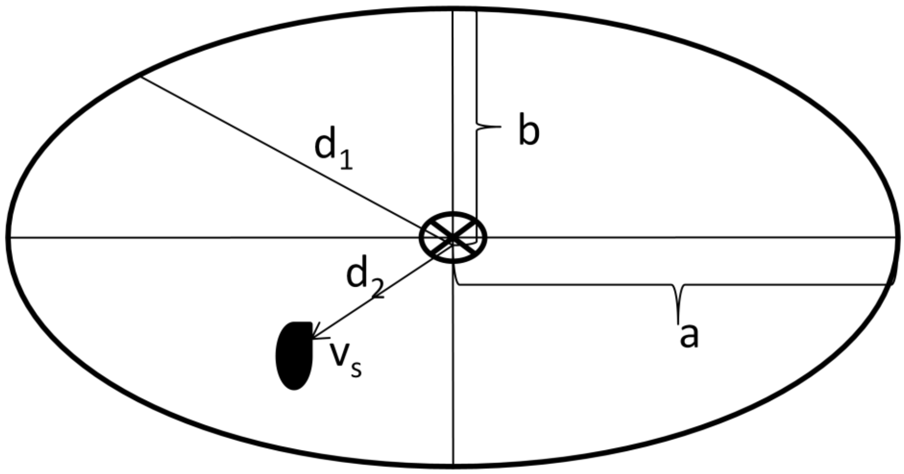


Figure 4.15. Elliptical Sea and Oil Spill Representation

There will be cleanup operation for the oil spill. Oil spill response will take off from the peripheral line of the ellipse.

First, response team will go to accident location then to oil spill center. Total time needed for arriving to oil spill is called T_t and it equals to the sum of arrival time to accident location (T_1) and arrival time from accident location to oil spill center (T_2).

$$T_t = T_1 + T_2 \tag{4.6}$$

$$F_T\left(T_1, T_2\right) = \iint_{-\infty}^{\infty} f_{12}(T_1, T_2)\, dT_1 dT_2 \tag{4.7}$$

where,

$f_{12}(T_1, T_2)$is joint probability density function of T_1& T_2.

$$T_1 = d_1 \times v_b \tag{4.8}$$

where,

d_1=distance from station to accident place which is changing from “b” to “a” with a uniformly distributed function.

<u>4.8.2.1. Case 1:</u> Assume that d_1 and v_s are uniformly distributed.

f_{d1} is the probability density function of response distance.

$$f_{d1}\left(d_1\right) = \frac{1}{(a-b)} \tag{4.9}$$

$$f_1\left(T_1\right) = f_d\,(d)\Big|_{d=v_b T_1} \left|\frac{\partial h_1}{\partial T_1}\right| \tag{4.10}$$

$$f_1\left(T_1\right) = \frac{1}{a-b} v_b \tag{4.11}$$

$$T_2 = \frac{T_1 v_s}{v_b} \tag{4.12}$$

$$d = h_1\left(T_1, T_2\right) = v_b T_1 \tag{4.13}$$

$$v_s = h_2\left(T_1, T_2\right) = \frac{v_s T_2}{T_1} \tag{4.14}$$

$$f\left(d, v_s\right) = f_d\left(d\right).f_{v_s}\left(v_s\right) = \frac{1}{a-b} \times \frac{1}{2} \tag{4.15}$$

$$g(T_1,T_2) = f(d,v_s)\Big|_{\substack{d=h_1(T_1,T_2) \\ v_s=h_2(T_1,T_2)}} |J| \tag{4.16}$$

where,

$$|J| = \begin{vmatrix} \frac{\partial h_1}{\partial T_1} & \frac{\partial h_1}{\partial T_2} \\ \frac{\partial h_2}{\partial T_1} & \frac{\partial h_2}{\partial T_2} \end{vmatrix} \tag{4.17}$$

$$g(T_1,T_2) = \frac{1}{2a-2b} \begin{vmatrix} v_b & 0 \\ -\frac{T_2 v_b}{T_1^2} & \frac{v_b}{T_1} \end{vmatrix} \tag{4.18}$$

$$g(T_1,T_2) = \frac{v_b^2}{2T_1(a-b)} \tag{4.19}$$

$$E[T_1+T_2] = \int_0^{a/v_b} \int_0^{T_1 v_s / v_b} (T_1+T_2) g(T_1,T_2)\, dT_2\, dT_1 \tag{4.20}$$

$$E[T_1+T_2] = \int_0^{a/v_b} \int_0^{T_1 v_s / v_b} (T_1+T_2) \frac{v_b^2}{2T_1(a-b)}\, dT_2\, dT_1 \tag{4.21}$$

<u>4.8.2.2. Case 2:</u> Assume d_1 is uniformly distributed and v_s is Rayleigh distributed as found in section 4.3.

$$f(v_s) = \frac{v_s}{b^2} e^{\left(\frac{-v_s^2}{2b^2}\right)} \tag{4.1}$$

where,

b=0.663114 ≅ 0.66

Equations from (4.7) to (4.15) are valid for this problem.

$$g(T_1,T_2) = \frac{1}{2(a-b)} \frac{v_s}{(0.66)^2} e^{\left(\frac{-v_s^2}{2(0.66)^2}\right)} \begin{vmatrix} v_b & 0 \\ -\frac{T_2 v_b}{T_1^2} & \frac{v_b}{T_1} \end{vmatrix} \tag{4.22}$$

$$g\left(T_1,T_2\right)=\frac{v_s {v_b}^2}{0.87(a-b)T_1}e^{\left(\frac{-{v_s}^2}{0.87}\right)} \tag{4.23}$$

$$E[T_1+T_2]=\int_0^{a/v_b}\int_0^{T_1 v_s/v_b}(T_1+T_2)g(T_1,T_2)dT_2dT_1 \tag{4.24}$$

$$E[T_1+T_2]=\int_0^{a/v_b}\int_0^{T_1 v_s/v_b}(T_1+T_2)\frac{v_s {v_b}^2}{0.87(a-b)T_1}e^{\left(\frac{-{v_s}^2}{0.87}\right)}dT_2dT_1 \tag{4.25}$$

5. NUMERICAL SOLUTION MODEL FOR MARMARA SEA

ERS should be located at the nearest place to accident location at Marmara Sea to minimize the response time. When 1282 maritime accidents from 1979 to 2007 at Marmara Sea is observed, it is understood that, accident place, time and sea conditions (current and wind) cannot be predicted as a deterministic process. But probability of accident locations can be predicted depending on past records.

The present model uses accident probability distribution, current and wind data (as probability, magnitude and direction) at Marmara Sea, and velocity of response vessel.

5.1. Assumptions

It is assumed that there is a maritime accident over the Marmara Sea. After the maritime accident occurs there is an oil spill. Oil slick moves by means of wind and current. Oil propagates along the resultant vector of current and wind vectors, 100% and 3% respectively.

No simultaneous maritime accident is assumed. If historical maritime accident data is observed, this assumption becomes realistic. Also according to calculated accident probability data, most probable simultaneous accident probability is 1.13E-09 which is a very low chance.

Data for accident probability does not change according to weather conditions at the calculations. It is known that weather conditions have an effect on accident probability but data is taken from TUBITAK as calculated value. Also exact accident time and place cannot be predicted so taking accident probability as a deterministic value is not a big problem.

According to regulations all of the accidents with oil spill must have response. Response will be done from one ERS. In catastrophic conditions more than one ERS can help to cleanup operations but first arrival boat's response time is considered at the calculations.

5.2. Probability Based Optimization

In this section, methodology is constructed and applied to place ERS at the coast of Marmara Sea. For weighing the importance of cells, accident probability is used. "I" symbolizes potential accident place set at sea and size of the set is shown with "m". w_i symbolizes the accident probability of the nodes at set "I". "J" symbolizes potential ERS node set and the size of the set is shown with "n".

Distance calculations between sea grids and ERS are calculated as Euclidean (straight-line distance metric). Equation (5.1) shows distance calculation.

$$d[(x_1, y_1);(x_2, y_2)] = \sqrt[2]{(x_1 - x_2)^2 + (y_1 - y_2)^2} \quad (5.1)$$

Arrival time from all potential ERS to each sea grid for every condition is calculated. Results are stored in T_g matrix.

$$T_t = T_1 + T_2 \quad (5.2)$$

where,
T_t= arrival time from station to slick
T_1= arrival time from station to cell
T_2= time from cell to oil slick

$$T_g\left[x_j, v_i, l\right] = \frac{d^l\left(x_j, v_i\right)}{boatspeed} + \frac{\left(\dfrac{d^l\left(x_j, v_i\right)}{boatspeed} \times p\left(i, l\right)\right)}{boatspeed} \quad (5.3)$$

$\forall i$ this equation is calculated; where,
x_j=symbolizes j^{th} potential station
v_i=symbolizes i^{th} cell
l =symbolizes the different condition (wind & current) l={1,2,…,s}

$d^l(x_j, v_i)$ =is the direct distance between x_j node and v_i node at condition l.

$p(i, l)$ = movement vector of petroleum in grid “i” at condition “l”

Petroleum vector is

$$\vec{p}(i,l) = \vec{c}(i,l) + 0.03\vec{w}(i,l) \tag{5.4}$$

where,

$\vec{w}(i, l)$ = wind vector in l^{th} condition i^{th} cell

$\vec{c}(i, l)$ =current vector in l^{th} condition at i^{th} cell

Results are multiplied with the corresponded probabilities.

$$T_o\left[x_j, v_i\right] = \sum_{l=1}^{s} w_i \times k^l \times T_g\left[x_j, v_i, l\right] \tag{5.5}$$

$\forall i$ calculations are done, where,

w_i = symbolizes finite number of sea cell’s accident probability

k^l =symbolizes probability of l^{th} condition

The value of the summation is stored in T_o matrix and gives weighted arrival time from j^{th} ERS to i^{th} cell in expected conditions. Also summation helps to decrease the dimension of the matrix from 3 to 2, which makes selection easier.

5.2.1. Solution

5.2.1.1. One Station Case: Rows and columns of the matrix T_o, represent potential ERS positions and sea cells respectively. If the values of the row are summed up, it gives the expected response time of the associated ERS and a ERS vector is created.

$$ERS(j) = \sum_{i=1}^{m} T_o\left[x_j, v_i\right] \quad , \forall j \tag{5.6}$$

where,

i: symbolizes the finite number of sea cell (possible accident locations)

m: symbolizes the size finite number of sea cell, i€I={1,2,....,m}

In order to decide the location of one station, ERS with the minimum arrival time from ERS(j) vector is selected.

5.2.1.2. More Than One Station: An optimization has to be done, for locating more than one ERS. $T_o[x_j,v_i]$ matrix will be used for ERS combinations. Objective function is defined as:

$$\min[T_0]\left|x_j\right| = \begin{pmatrix} t_{11} & \cdots\cdots & t_{1n} \\ \vdots & \ddots & \vdots \\ \vdots & t_{ij} & \vdots \\ \vdots & \ddots & \vdots \\ t_{m1} & \cdots\cdots & t_{mn} \end{pmatrix} \begin{vmatrix} x_1 \\ \vdots \\ x_n \end{vmatrix} \tag{5.7}$$

$$\min\max\sum_{j=1}^{n}\sum_{i=1}^{m} t_{ji}x_{ji} \tag{5.8}$$

Equation (5.8), is solved under given constraints

$$\sum_{j=1}^{n} x_{ji} = 1, \forall i \tag{5.9}$$

where,

$$x_{ji} = \begin{cases} 1, & \text{if there is reponse from jth station to ith cell} \\ 0, & \text{if there is no response} \end{cases}$$

$i \in I$ only one ERS respond to i^{th} cell.

$$y_j \geq x_{ji} \tag{5.10}$$

Equation (5.10) is a constrain, which means there will be response from j^{th} node to i^{th} cell if and only if there is ERS at j^{th} node and $j \in J$.

$$y_j = \begin{cases} 1, & \text{if there is ERS at jth node} \\ 0, & \text{if there is no ERS at jth node} \end{cases}$$

$$\sum_{j=1}^{n} y_j = p \tag{5.11}$$

equation (5.11) limits the number of ERS.

p: number of ERS that will be located $1 \le p \le n$

equation (5.9), (5.10), (5.11)

The solution of equation (5.8) gives location of desired number of ERS.

Model is deciding if there will be ERS at possible node or not. When there is ERS y_i gets 1, if not it gets 0, so it is a binary problem. In MATLAB optimization toolbox there is Binary Integer Programming function called "bintprog". This function minimizes objective function, ($\min f.x$) by giving 0 and 1 to x vector according to constrains

$$[A]|x| \le |b| \tag{5.12}$$

$$[Aeq]|x| = |beq| \tag{5.13}$$

In the solution of the model T_0 matrix is the "f" function. So T_0 is reshaped as a vector for the calculations and shown in equation 5.14.

$$\begin{pmatrix} t_{11} & \cdots\cdots & t_{1n} \\ \vdots & \ddots & \vdots \\ \vdots & t_{ij} & \vdots \\ \vdots & \ddots & \vdots \\ t_{m1} & \cdots\cdots & t_{mn} \end{pmatrix} \cong |t_{11}\, t_{21} \quad t_{31} \quad \ldots t_{m1}\, t_{12} \quad t_{22} \ldots \quad \ldots \quad t_{ij} \quad t_{1n} \quad \ldots t_{mn}| = |T| \tag{5.14}$$

Also x vector has to be modified according to $|T|$, and modified x vector is given at equation 5.15

$$|x| = |x_{11} \quad x_{21} \quad \ldots \quad x_{m1} \quad \ldots x_{ij} \quad \ldots \quad x_{1n} \quad \ldots x_{mn}| \tag{5.15}$$

Equations from (5.9) to (5.11) are constrains of the model. In Equation (5.10), there is y_i parameter; it has to be put in the solution. Some modification has to be done to T and x vector, in order to put this variable into equations

x vector is extended and y_i parameter is put at the expanded parts. Also T vector has to be extended and coefficients at the extended part should be 0 in order not to change the value of the objective function. Euqation 5.16 and 5.17 represents the modified form of T vector and x vector respectively.

$$|T| = \left| t_{11}\, t_{21} \quad t_{31} \quad \ldots t_{m1}\, t_{12} \quad t_{22} \ldots \quad \ldots \quad t_{ij} \quad t_{1n} \quad \ldots t_{mn} \quad t_{y1} \quad \ldots \quad t_{ym} \right| \tag{5.16}$$

$$|x| = |\, x_{11} \quad x_{21} \quad \ldots \quad x_{m1} \quad \ldots x_{ij} \quad \ldots \quad x_{1n} \quad \ldots x_{mn} \quad y_1 \quad \ldots \quad y_m \,| \tag{5.17}$$

There are two types of constrains in the model. One of them is equality type $(=)$ and the other is smaller or equal to type $(\leq)$.

Equality type constrains are equations (5.9) and (5.11). Summation type equations are written as matrix and put into “bintprog” function as $[Aeq]|x| = |beq|$. Equation (5.18) shows the constrain.

$$\begin{bmatrix} a_{11} & \cdots & a_{1(m\times n+m)} \\ \vdots & \ddots & \vdots \\ a_{(n+1)1} & \cdots & a_{n(m\times n+m)} \end{bmatrix} \begin{vmatrix} x_{11} \\ \vdots \\ x_{m\times n} \\ y_1 \\ \vdots \\ y_m \end{vmatrix} = \begin{vmatrix} b_1 \\ \vdots \\ b_{n+1} \end{vmatrix} \tag{5.18}$$

where,

at i^th^ row from $a_{i((i-1))*m)}$ to $a_{i(i*m)}$ it takes 1 and other takes 0.

First nth row of Aeq matrix and beq vector provide constrain $\sum_{j=1}^{n} x_{ji} = 1, \quad \forall i$ and the (n+1)th row of the Aeq matrix and beq vector provide $\sum_{j=1}^{n} y_j = p$ constrain.

Smaller or equal to type constrains is Equation (5.10) . Summation type equations are written as matrix and put into "bintprog" function as $[A]|x| \le |b|$. Equation (5.19) shows inequality constrain.

$$\begin{bmatrix} a_{11} & \cdots & a_{1(m\times n+n)} \\ \vdots & \ddots & \vdots \\ a_{(m\times n)1} & \cdots & a_{(m\times n)(m\times n+n)} \end{bmatrix} \begin{vmatrix} x_{11} \\ \vdots \\ x_{m\times n} \\ y_1 \\ \vdots \\ y_m \end{vmatrix} \le \begin{vmatrix} b_1 \\ \vdots \\ b_{m\times n} \end{vmatrix} \tag{5.19}$$

where,
in the A matrix there is a big (m*n)by (m*n) identity matrix and the left part (from (m*n)th column to (m*n+n)th column) consist of repetition of n by n identity matrices. b vecxtor contains zeros at its row. Matrix "A" and b vector "b" provides $y_j \ge x_{ji}$, constrain.

5.2.2. Location of Emergency Response Stations:

By means of Equation (5.3), arrival time from a potential ERS to center of an oil spill in every condition is found. In Equation (5.5) average value of conditions are calculated. When all arrival time for one station is summed up as in Equation (5.6), weighted arrival time for one ERS to all cells is found and it is represented in Figure 5.1.

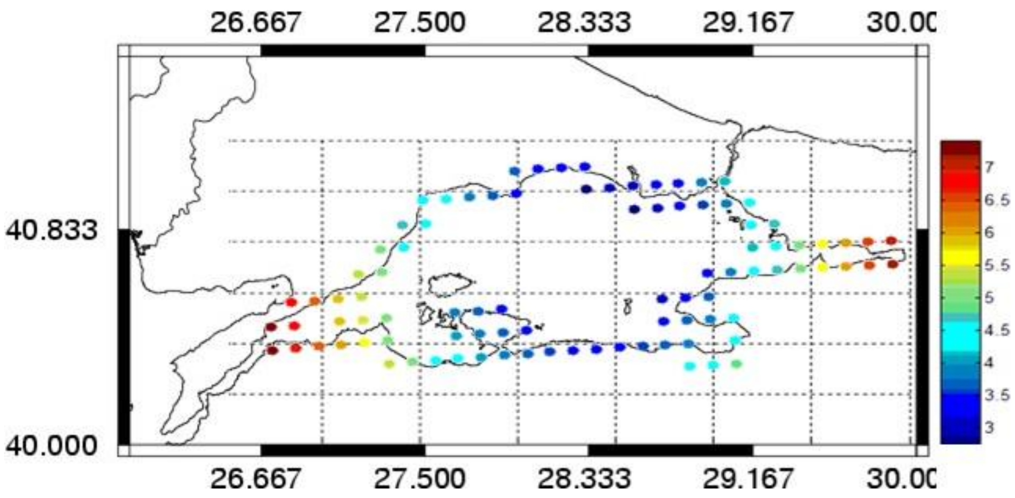


Figure 5.1. Expected response time of potential station nodes in terms of hour (for 1 ERS and probability based case)

In Figure 5.1 it is seen that response time of potential ERS is smaller at the eastern part of the middle section of Marmara Sea. Accident probability is higher at Istanbul and Izmit Gulf and strong current (that increases the response time) from Bosphorus are the main causes that effect the expected response time.

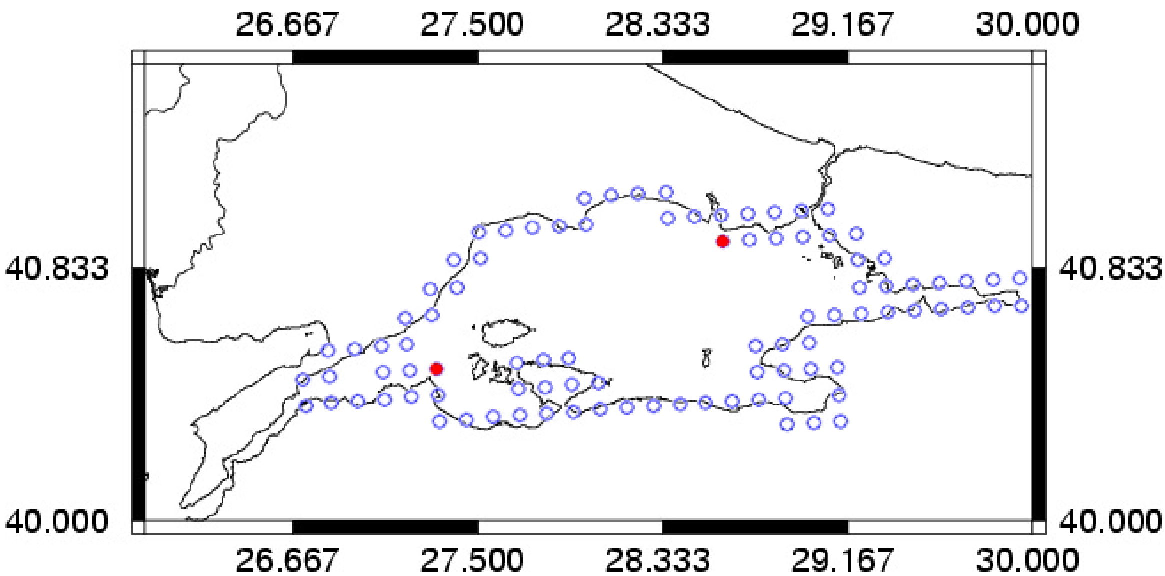


Figure 5.2. Optimum location of 2 ERS (probability based)

Figure 5.2. shows that if two ERS is located, they should be located at Karabiga and Büyükçekmece. These places are close to entrance of the straits.

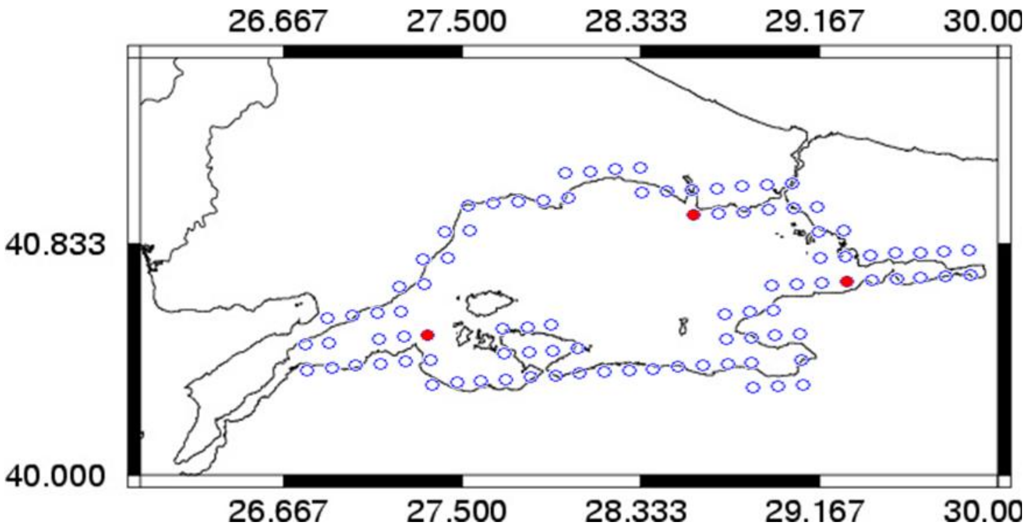


Figure 5.3. Optimum location of 3 ERS (probability based)

In Figure 5.3. it is seen that, stations are located like a triangle which covers Marmara Sea. High accident probability regions (entrance of Istanbul strait and Izmit Gulf) and also eastern part of middle of Marmara Sea with lower accident probability are covered by Istanbul and Yalova Emergency Response Stations. Other station at Karabiga can have quick response to entrance of Çanakkale Strait and around Marmara Island.

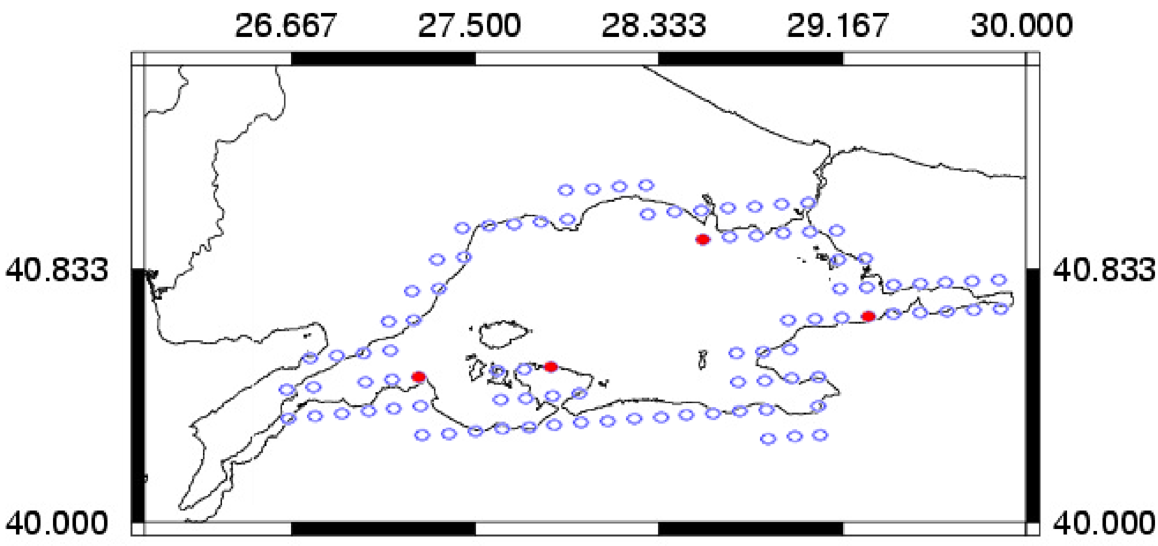


Figure 5.4. Optimum location of 4 ERS (probability based)

In Figure 5.4. four ERS are located. Three of the stations are at the same place and one more station is located to Kapıdağ. The last added station has a chance to make quick response to middle part of the Marmara Sea.

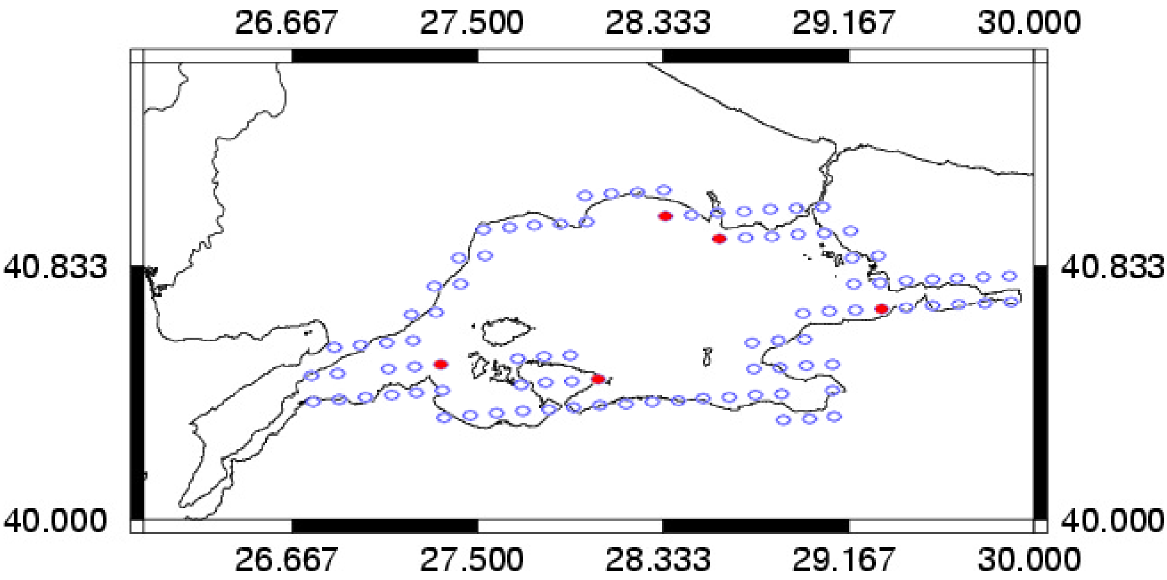


Figure 5.5. Optimum location of 5 ERS (probability based)

In Figure 5.5. five ERS are located. First four of them at the same place and the last one is located to Silivri. The most important thing about Silviri is, it is near to Marmara Ereğlisi where it contains natural gas storage facilities. Natural gas is transported by means of ships. That means there is an extra maritime traffic at Marmara Ereğlisi.

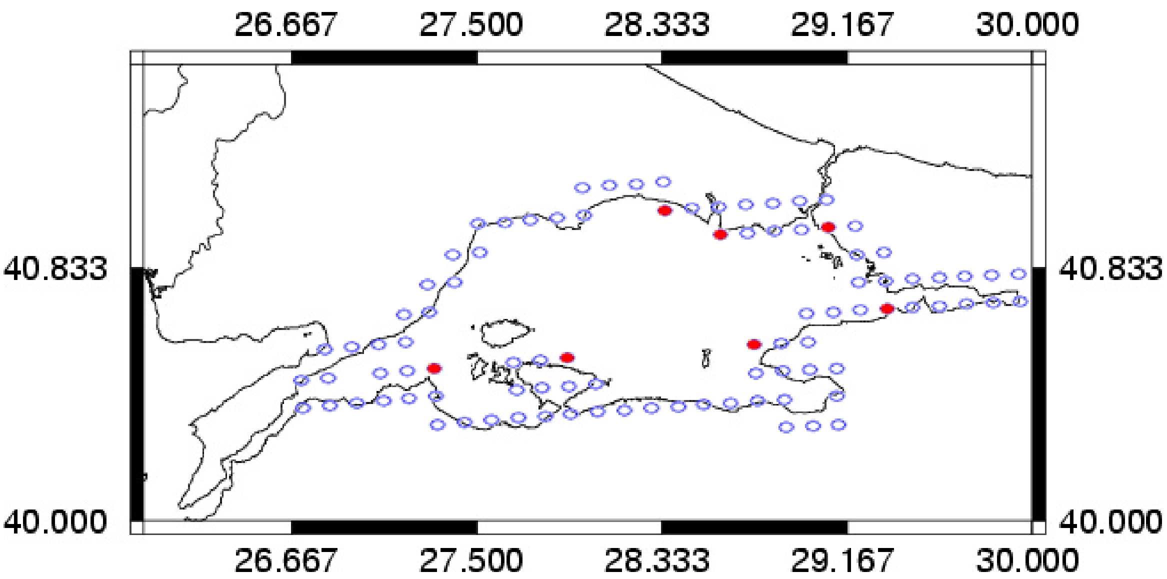


Figure 5.6. Optimum location of 7 ERS (probability based)

Seven stations are located and shown in Figure 5.6. First five of them at the same place and the last two of them located to Kadıköy and Armutlu. Kadıköy is the entrance of İstanbul strait and located station can have a very quick response to spilled oil at the strait. Armutlu is near to Mudanya. Mudanya has an increasing maritime traffic, because of its harbor used by Bursa’s industry.

5.2.3. Computational Time

Computational time is important in these type of projects. Because, computer’s memory may not be able to solve problems after some modifications are done at the algorithm. One modification for Marmara Sea can be increase in number of ERS.

Problem solved for 3,4,5 and 7 ERS location and computational time needed for solving the problem is given at Table 5.1.

Table 5.1. Computational Time Table for Probability Based Solution

Probability Based Solution				
number of stations (p)	3	4	5	7
run time (sec)	68.39235	51.74094	39.4404	32.68856

According to Table 5.1., as the number of stations increases run time for computer decreases.

5.3. Risk Based

At this part constructed methodology is applied to place ERS at the coast of Marmara Sea. For weighing the importance of cells accident risk is used.

Methodology is the same with probability based, expect accident probability data. Instead of accident probability data, risk data is used at Equation (5.5).

$$T_o\left[x_j,v_i\right]=\sum_{l=1}^{s} r_i \times k^l \times T_g\left[x_j,v_i,l\right] \tag{5.20}$$

$\forall i$ calculations are done, where,

r_i = symbolizes finite number of sea cell accident risk

5.3.1. Risk Based Solution

The main difference between probability based solution and risk based solution is the data that is used for cells. For probability based solution accident probability of the cell is use but for risk based solution accident risk of the cell is used for weighing the response time. Therefore equations at section 5.4 are valid at this section.

5.3.2. Location of Emergency Response Stations:

By means of Equation (5.3), arrival time from a potential ERS to center of an oil spill in every condition is found. In Equation (5.20) average value of conditions are calculated. When all arrival time for one station is summed up as in Equation (5.6), weighted arrival time for one ERS to all cells is found and it is represented in Figure 5.7.

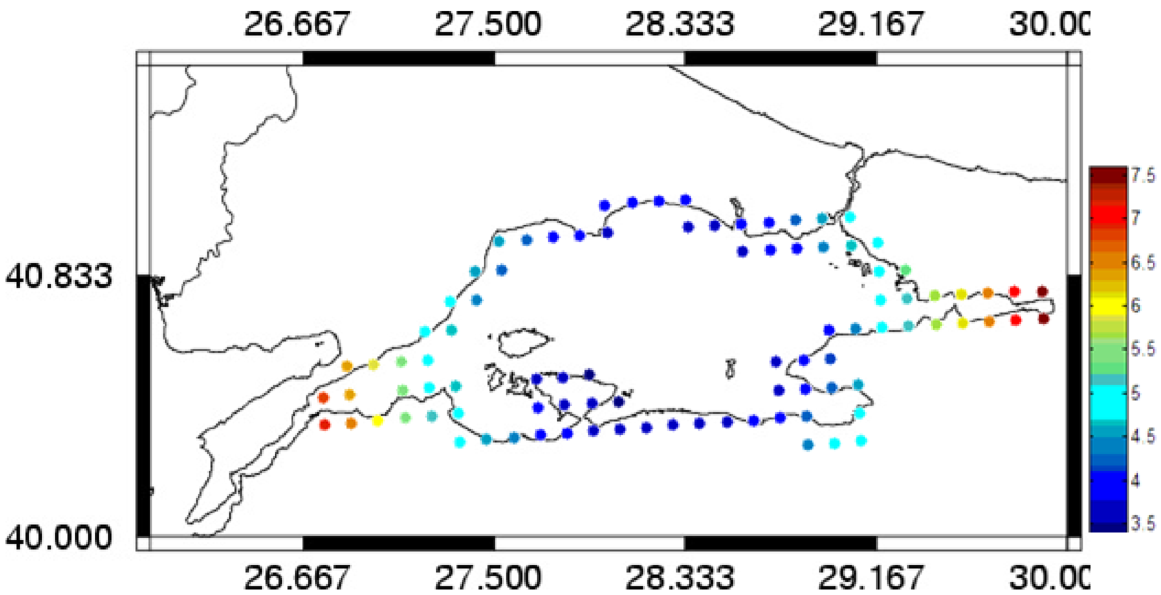


Figure 5.7. Expected response time of potential station nodes in terms of hour (for 1 ERS and risk based case)

In Figure 5.7. it is seen that response time of potential ERS is smaller at the middle section of Marmara Sea. Accident risk (Figure 4.13) is higher at the western, eastern and southern parts and also current drifts the oil spill towards southern direction. These are the main causes that effect the expected response time.

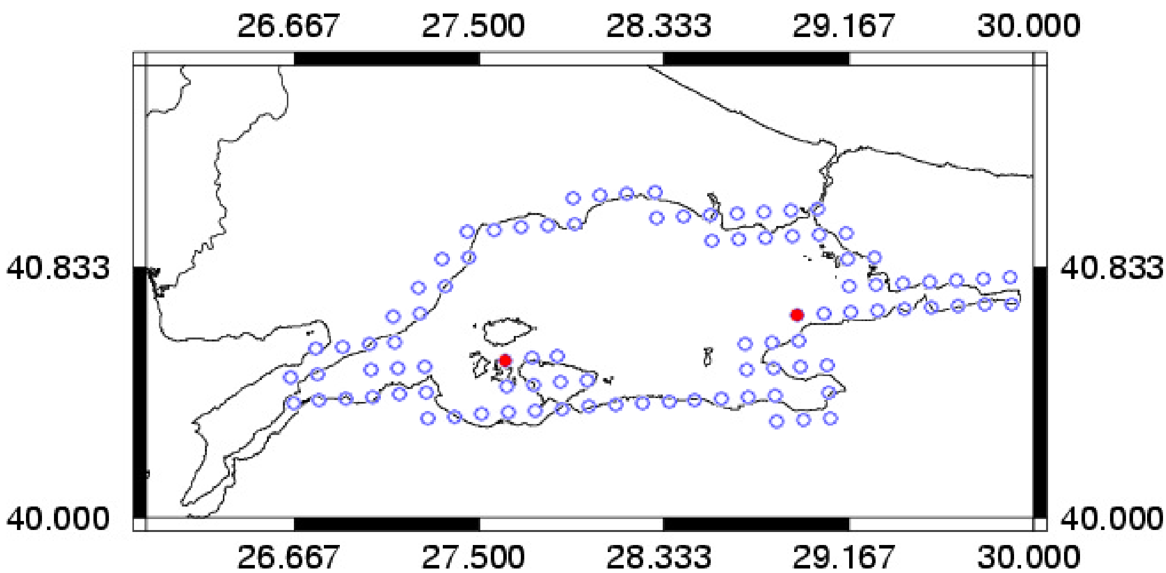


Figure 5.8. Optimum location of 2 ERS (risk based)

If two ERS is located, they will be situated as in Figure 5.8. One of them located at Kapıdağ Peninsula and the other is located at Çınarcık. They are placed as they are responding two equal part of Marmara Sea. Also both of them are located at the southern coast.

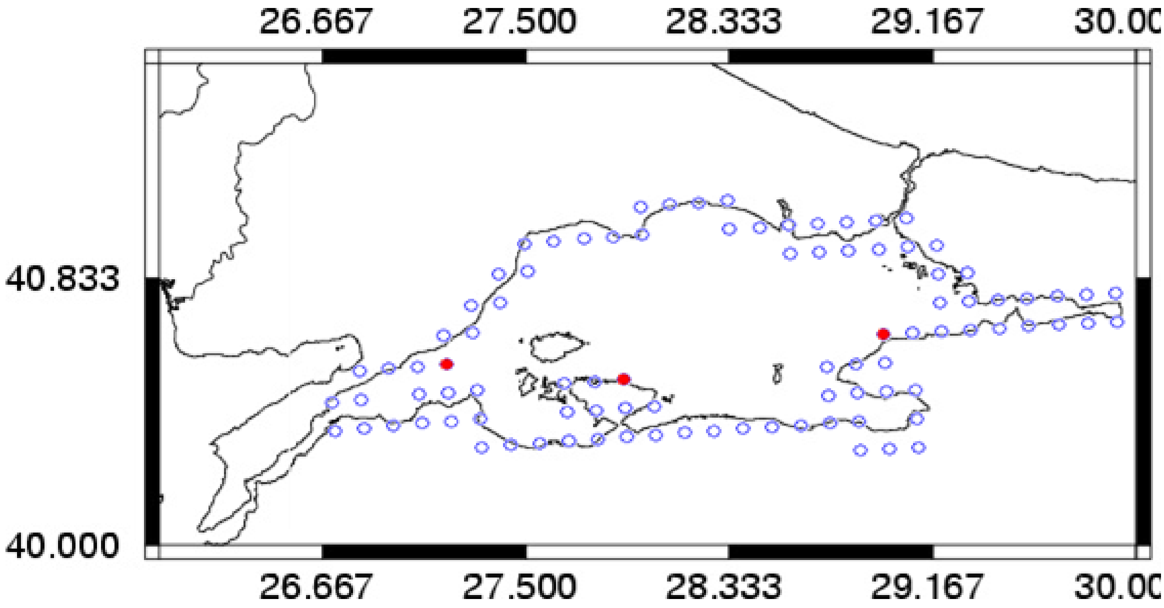


Figure 5.9. Optimum location of 3 ERS (risk based)

In Figure 5.9. it is seen that, stations are located like a line. The station’s place at Çınarcık does not change. Station at Kapıdağ Peninsula moves a little bit eastern part. The last station is located at Şarköy which can have a quick response to accidents at Çanakkale Strait and Marmara Islands.

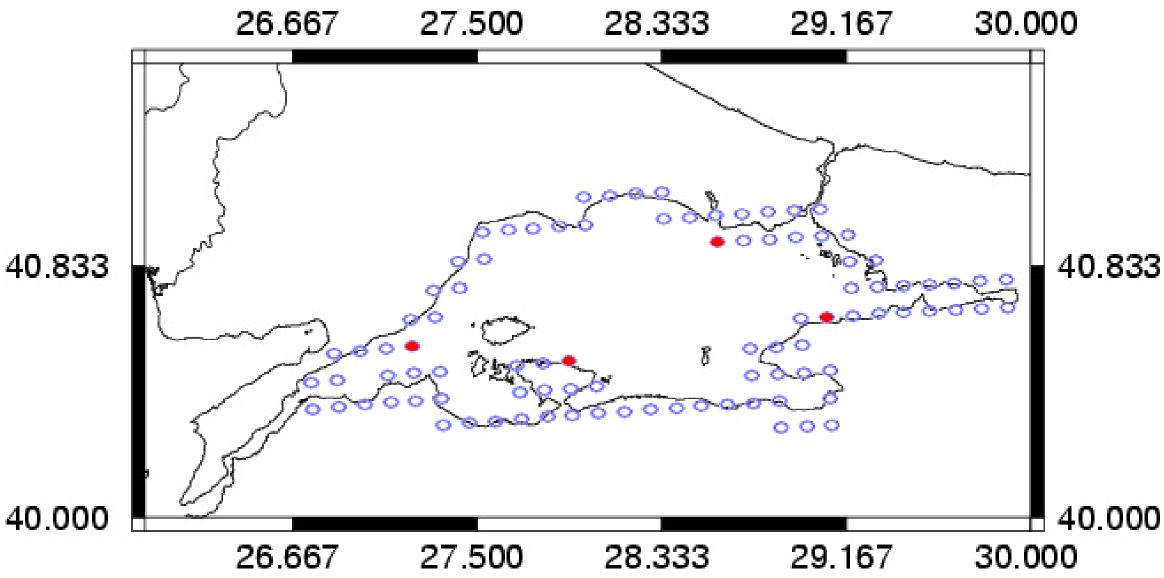


Figure 5.10. Optimum location of 4 ERS (risk based)

In Figure 5.10. represents placement of four ERS. Stations at Şarköy and Kapıdağ Peninsula are at the same place. Station at Çınarcık moved to Yalova. The last station added to Büyükçekmece. Fourth station has a capability respond to northern part of Marmara Sea.

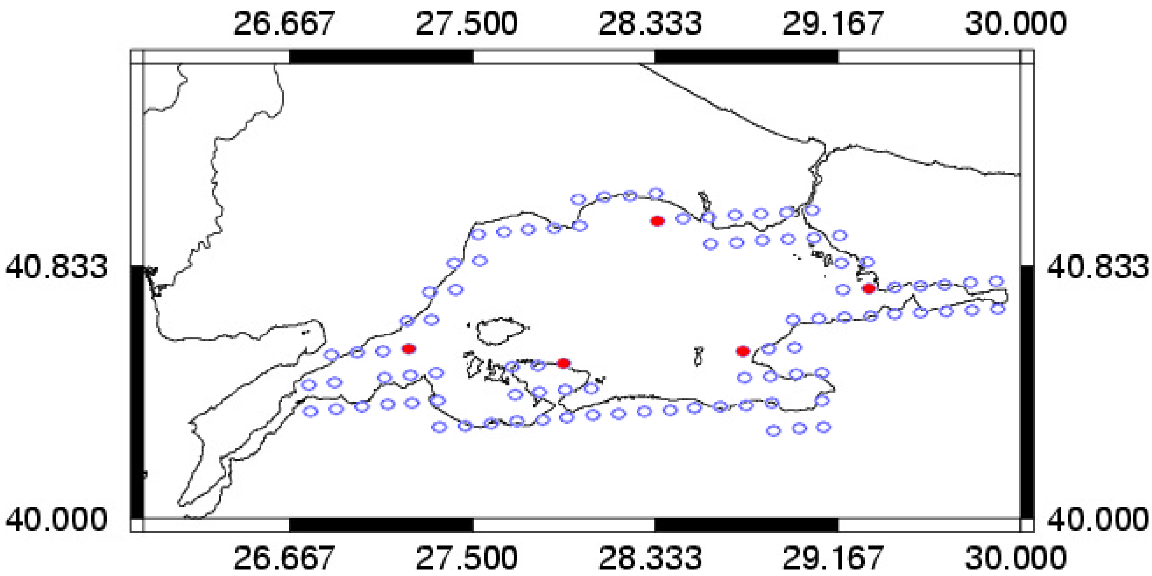


Figure 5.11. Optimum location of 5 ERS (risk based)

In Figure 5.11. locations of five ERS can be seen. Stations at Şarköy, Kapıdağ Peninsula are at the same place. The one at the Büyükçekmece moved to Silivri and it becomes closer to the middle section of Marmara Sea. Fourth one moved from Çınarcık to Armutlu which is closer to Mudanya. The last one is located to Gebze where the entrance of İzmit Gulf is.

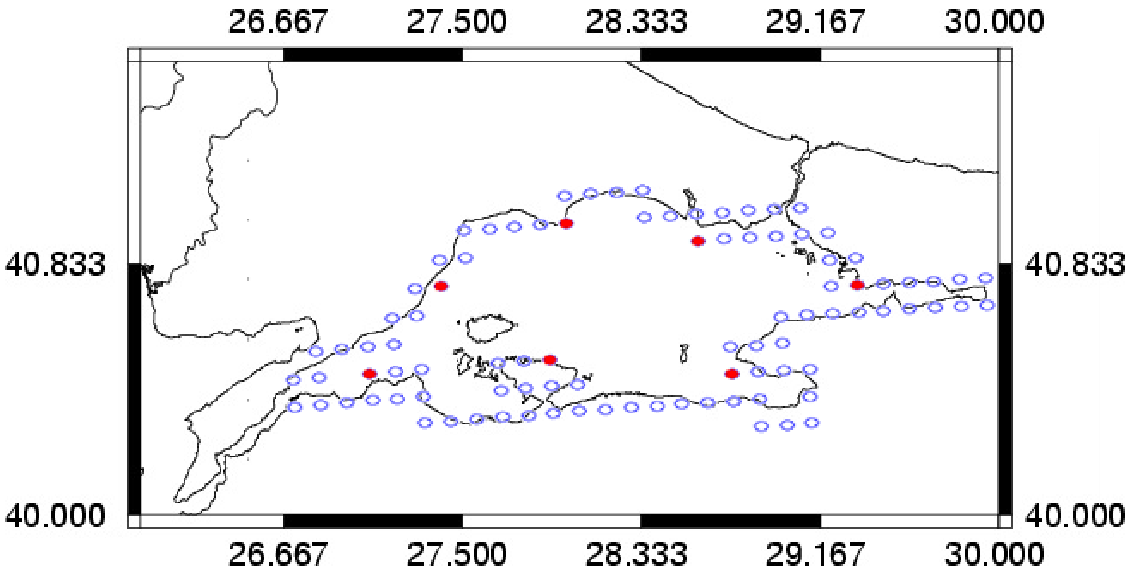


Figure 5.12. Optimum location of 7 ERS (risk based)

Seven stations are located and shown in Figure 5.12. From west to east first station is located at Karabiga but it becomes closer to the entrance of Çanakkale strait. Second one is located Tekirdağ, it can control the shipping traffic. Third one is located at Kapıdağ Peninsula. Fourth one is located at Marmara Ereğlisi. Fifth one is at Büyükçekmece. Sixth one is at Armutlu and the seventh one is at Gebze.

As the number of stations increases, they span over Marmara coast more evenly. First stations try to protect the southern coast of Marmara, because northerly wind and currents toward south direction are the most expected situations. Also accident risk is higher at the southern part of Marmara Sea. At some of the placement situations for accident risk, accident probability becomes important, in others accident impact. Since accident risk is the combination of accident probability and accident impact an exact explanation for the locations is impossible.

5.3.3. Computational Time

Problem solved for 3,4,5 and 7 ERS location and computational time needed for solving the problem is given in Table 5.2.

Table 5.2. Computational Time Table for Risk Based Solution

Risk				
number of stations (p)	3	4	5	7
run time (sec)	64.61046	87.52828	49.68067	57.80907

As the number of stations increases, run time of computer varying.

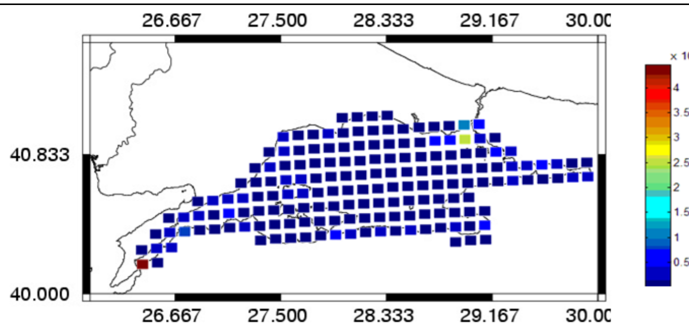
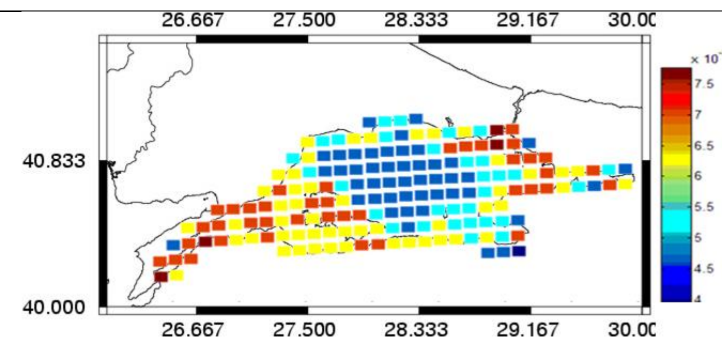
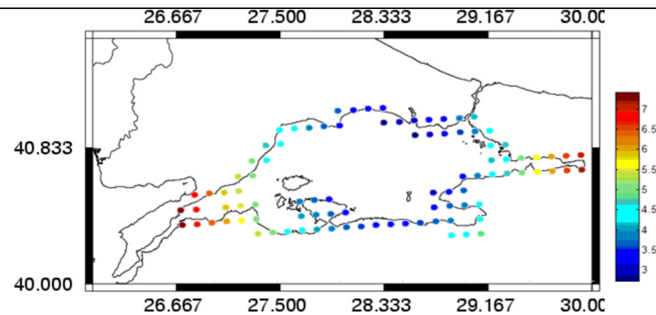
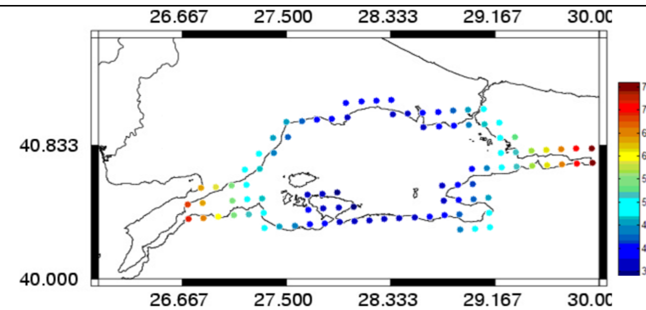
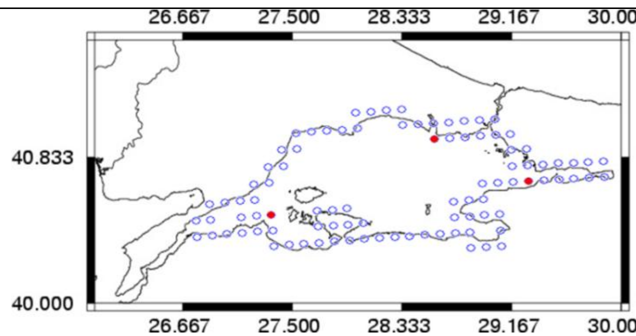
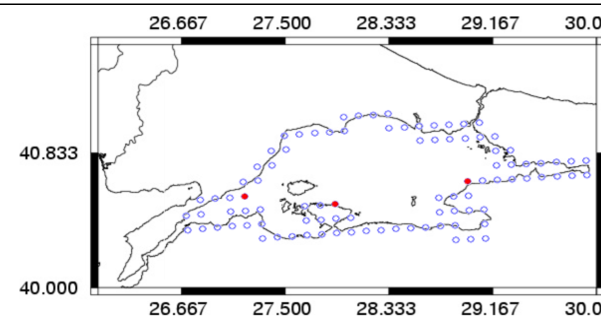
6. RESULTS AND DISCUSSION

At this section comparison of probability based results and risk based results will be done. Also effect of number of nodes on run time needed for placement of ERS will be discussed.

6.1. Comparison of Accident Probability Based Solution and Accident Risk Based Solution

There is a difference at the location stations when probability based and risk based solutions are studied. Table 6.1 is prepared for comparing purposes.

Table 6.1. Comparison of Accident Probability Based Solution and Accident Risk Based Solution

	Accident Probability Based	**Accident Risk Based**
Data		
Expected arrival time (one station solution)		
3 station solution		

Two solutions for optimum location of Emergency Response Stations are compared at Table 6.1. Data used for solutions is only differing at accident risk and accident probability. Other data (wind & current) are the same at both solutions.

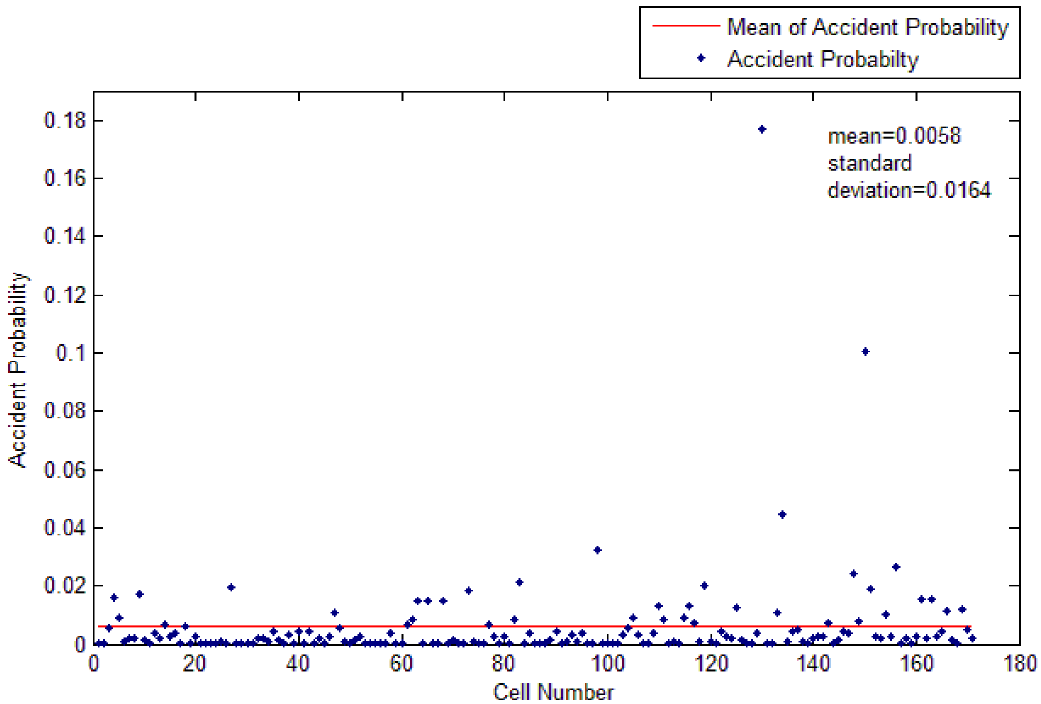


Figure 6.1. Accident Probability of Cells

Accident probability data is shown at the Figure 6.1. From the figure it is understood that most of the accident probability of cells are lower than mean and standard deviation supports this finding. Some of the cells have higher probabilities. From Figure 5.2. to Figure 5.6. shows that, locations of the ERS do not change as the number of stations increases. ERS located at 3 stations are also observed at 4,5 and 7 stations. This means that, peak accident probabilities have a big effect on the location of ERS.

Maritime accident risk at Marmara Sea can be observed from upper left cell of Table 6.1. It is observed that risk at the middle of sea is small when compared to entrance of straits. Also risk at the south coast of Marmara is higher than north coast.

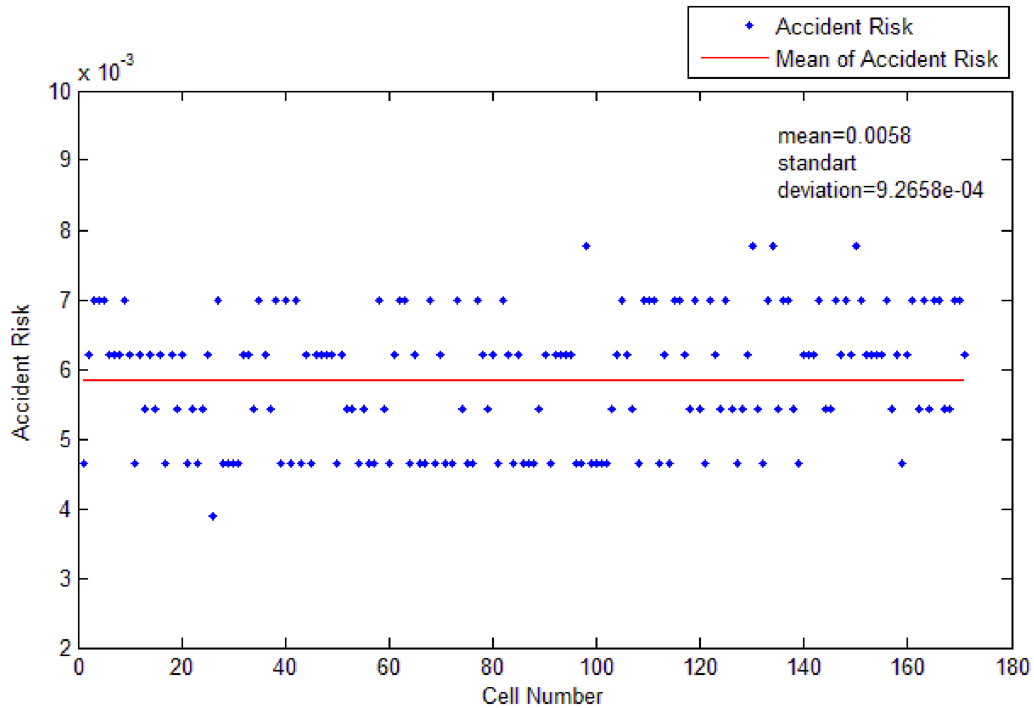


Figure 6.2. Accident Risk of Cells

In Figure 6.2. accident risk of cells are shown. It is observed that accident risk value of cells lay around the mean, also standard deviation is very small. So there is no big gap between accident risk of cells. From Figure 5.8. to Figure 5.12. locations for 2,3,4,5 and 7 stations are shown. As the number of stations increase, locations of the stations are changing.

From comparison at this section, it is understood that if the standard deviation of weighing parameter is high, peak values has a big effect on placement of the ERS.

6.2. Effect of Number of Nodes on Computational Time

Increase in number of nodes effects the location allocation calculation time. Number of nodes comes from two parameters, one of them is number of cells and the other is number of possible stations.

Number of cells are proportional to the division of the sea surface area by Δl^2. Number of stations are proportional to division of perimeter of sea by Δl.

$$n_t = n_s . n_c \tag{6.1}$$

where,
$n_t \cong$ number of situations
$n_s \cong$ number of stations
$n_c \cong$ number of cells

$$n_t = \frac{p.A}{\Delta l.\Delta l.\Delta l} = \left(\frac{L}{\Delta L}\right)^3 \tag{6.2}$$

$$t_r \propto \left(\frac{L}{\Delta L}\right)^3 \tag{6.3}$$

where,

n_s=ps/Δl

n_c=As/Δl

Δl ≅ distance between nodes

ps ≅ perimeter of sea

As ≅ area of sea

$t_r \cong$ run time

Equation (6.3) shows that run time for calculation part is proportional to the third power of number of nodes. When ΔL gets smaller number of nodes increases and run time for calculation increases.

In the project, cells are 10km*10km, so ΔL is 10 km. In the coming sections, ΔL is changed for 3, 5 and 7 station solutions. A graphical representation will be given and a fit test will be done in order to check if the finding at Equation (6.3) is true.

6.2.1. 3 station run time check

Table 6.2. Run Time Table for 3 Station

resolution (km)	1	10	20	30	40	50	60	70
run time (sec)	63010 (calculated)	50.30224	4.72259	1.711653	0.919752	0.79313	0.684736	0.609834

Table 6.2. is representation of run time for resolutions from 10km to 70km and 1km resolution is calculated for giving an idea for the future projects.

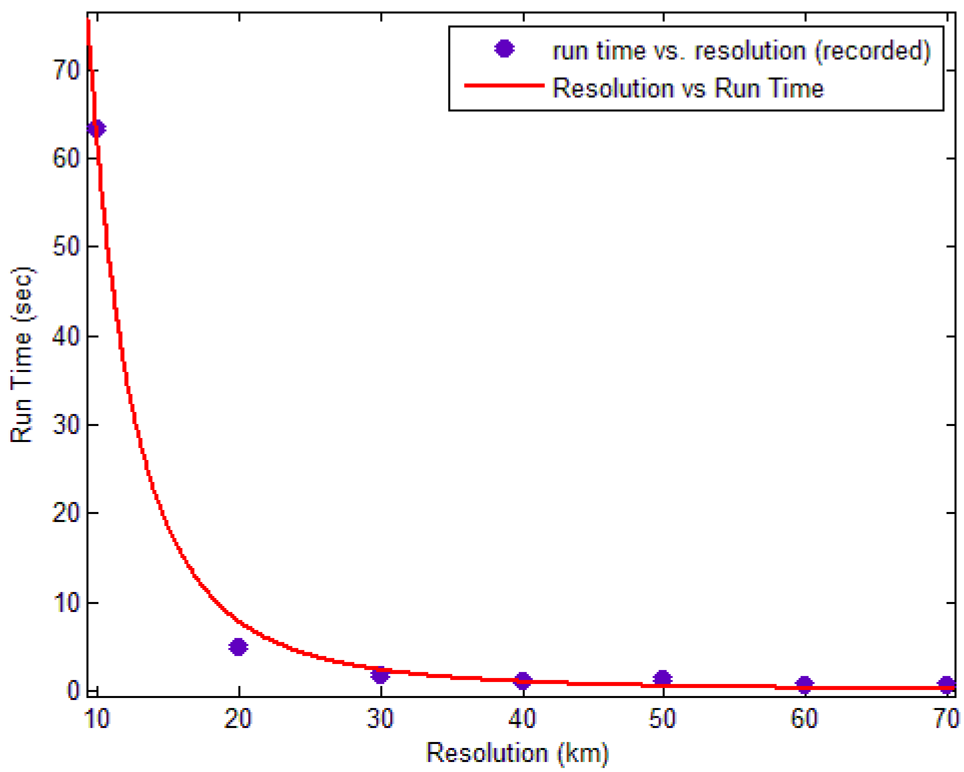


Figure 6.3. Run time vs Resolution (for 3 station)

Figure 6.3. shows the curve fitting of Equation (6.3) to recorded run time nodes. Below is the fitted curve's equation:

$$f(x) = a * x^b \tag{6.4}$$

Coefficients (with 95% confidence bounds):

a = 6.301e+004 (5.982e+004, 6.62e+004)

b = -3 (fixed at bound)

Goodness of fit test is done and result is given below:

σ^2 :0.9968

which is very near to 1 and it shows that results are very close to equation.

6.2.2. 5 station run time check

Table 6.3. Run Time Table for 5 Station

resolution (km)	1	10	20	30	40	50	60	70
run time (sec)	50110 (calculated)	50.30224	4.72259	1.711653	0.919752	0.79313	0.684736	0.609834

Table 6.3 is representation of run time for resolutions from 10km to 70km and 1km resolution is calculated for giving an idea for the future projects.

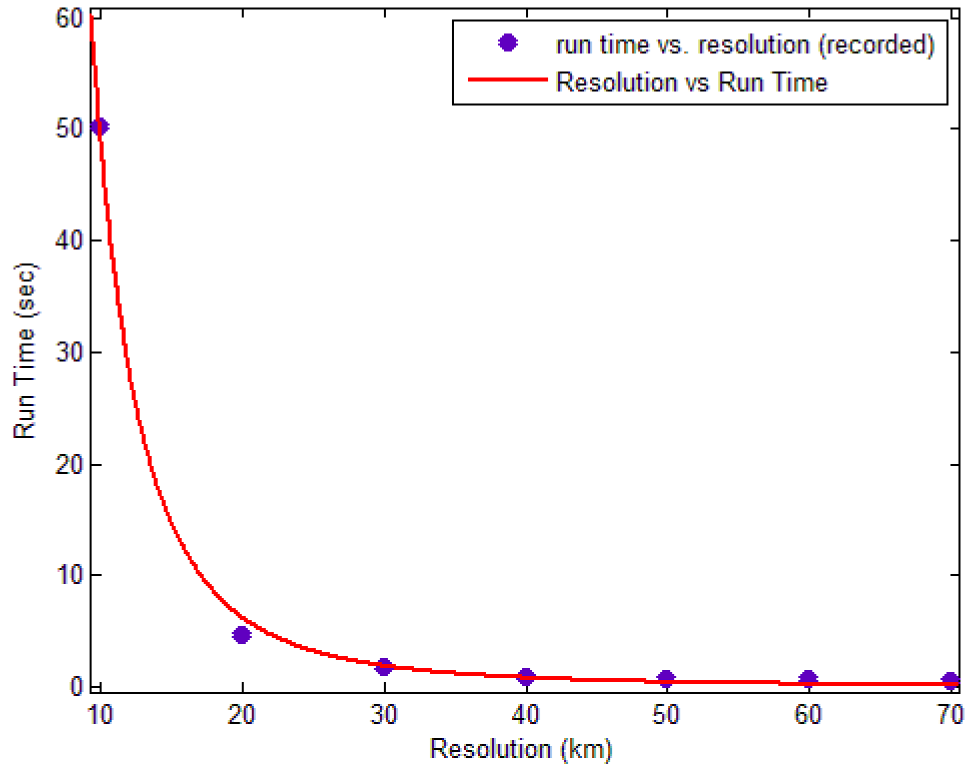


Figure 6.4. Run time vs Resolution (for 5 station)

Figure 6.4. shows the curve fitting of Equation (6.3) to recorded run time nodes. Below is the fitted curve's equation:

$$f(x) = a * x^b \tag{6.5}$$

Coefficients (with 95% confidence bounds):

a = 5.011e+004 (4.839e+004, 5.184e+004)

b = -3 (fixed at bound)

Goodness of fit:

σ^2: 0.9985

which is very near to 1 and it shows that results are very close to equation.

6.2.3. 7 station run time check

Table 6.4. Run Time Table for 7 Station

resolution (km)	1	10	20	30	40	50	60	70
run time (sec)	57810 (calculated)	58.08866	5.072671	1.657562	0.868246	0.792546	0.677972	0.613243

Table 6.4. is representation of run time for resolutions from 10km to 70km and 1km resolution is calculated for giving an idea for the future projects.

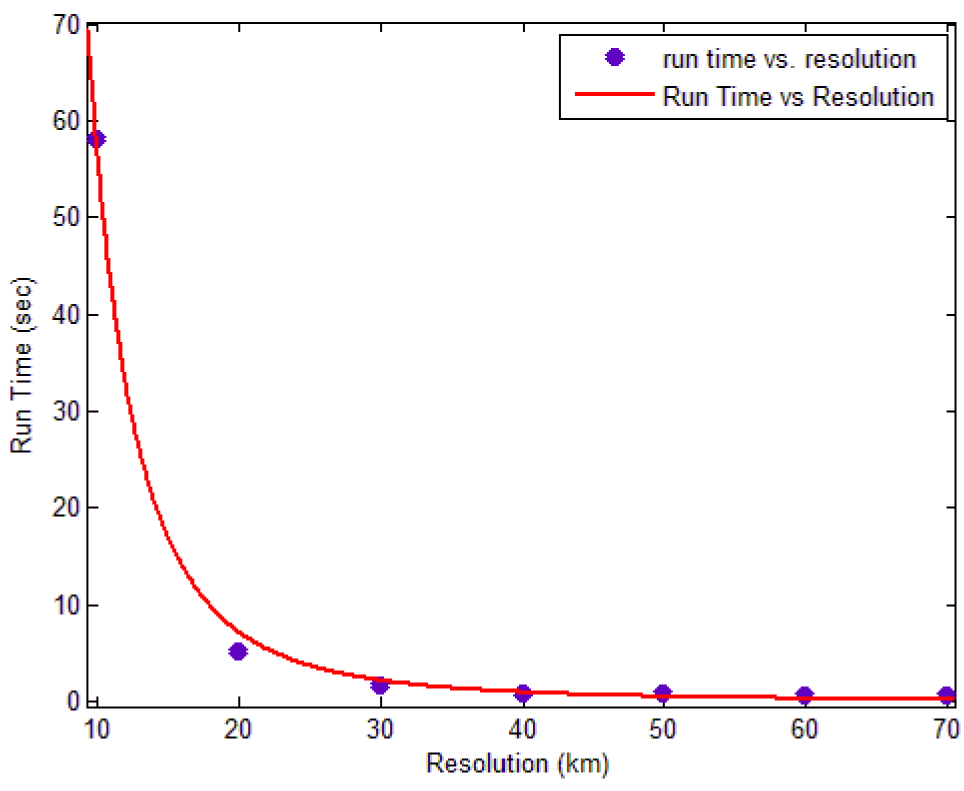


Figure 6.5. Run time vs Resolution (for 7 station)

Figure 6.5. shows the curve fitting of Equation (6.3) to recorded run time nodes. Below is the fitted curve's equation:

$$f(x) = a * x^b \tag{6.6}$$

Coefficients (with 95% confidence bounds):

a = 5.781e+004 (5.55e+004, 6.011e+004)

b = -3 (fixed at bound)

Goodness of fit:

σ^2 : 0.998

which is very near to 1 and it shows that results are very close to equation.

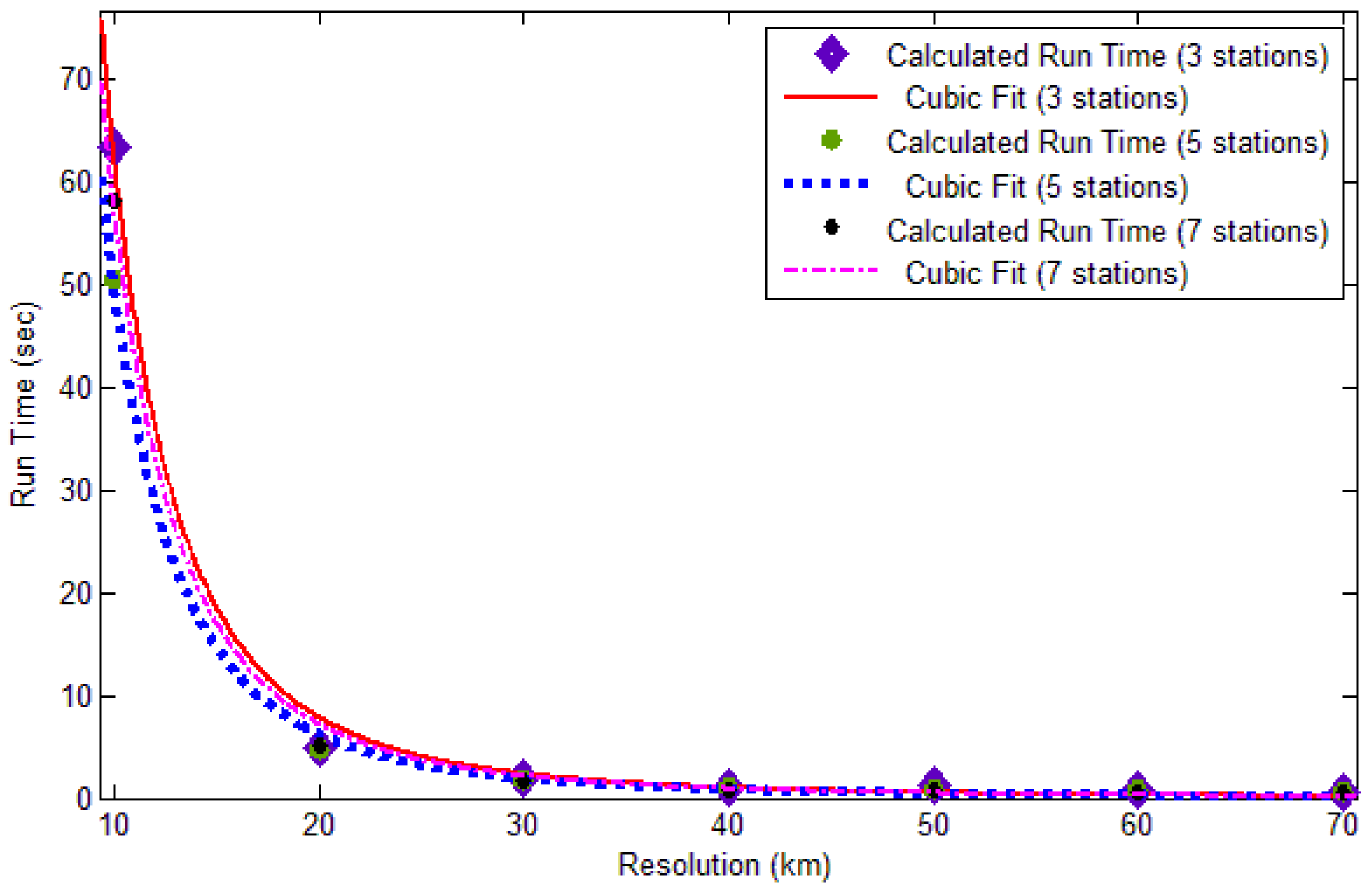


Figure 6.6. Comparison of curve fits for 3,5 and 7 stations

Figure 6.6. shows that, Equation (6.3) is valid for 3, 5 and 7 stations. Also σ^2 values are supporting the results. At bigger projects decreasing number of stations can be solution for finding the location of stations and also for run time efficiency.

6.3. Other Solution Functions

Besides "bintprog" function of Matlab, "fmincon" function is used for the solution of the model. The main difference between "bintprog" and "fmincon" is the range of solution set. In "bintprog" only "0" and "1" are tried for the solution set, but in "fmincon" solution set can be bounded by user as desired.

In this study, decision of opening a facility is taken. Therefore, range is bounded between "0" and "1", also decision variables are restricted to be "0" or "1".

$$0 \le x \le 1 \tag{6.7}$$

$$y = 0,1 \tag{6.8}$$

Equation (6.7) and (6.8) are the representation of the bounds of the model. Other constrains for "fmincon" are the same with "bintprog". For comparing both functions and imaginary situation is created. In this imaginary situation there is 5 demand points and 3 possible facility locations. In Table 6.5. distance between demand points and possible facility locations are given.

Table 6.5. Imaginary Situation for Comparison of Functions

	demand points				
possible facility locations	3	5	8	14	7
	1	12	32	3	9
	6	21	1	5	11

Values in Table 6.5 are used as inputs for both functions. In Table 6.6. there is a comparison of results and run time of both functions.

Table 6.6. Comparision of "bintprog" and "fmincon" functions

function type		bintprog		fmincon
x(i,j)	1,1	1		1
	2,1	0		-2.78E-17
	3,1	0		2.47E-32
	1,2	1		1
	2,2	0		-1.85E-16
	3,2	0		1.23E-32
	1,3	0		1.71E-16
	2,3	0		-1.23E-32
	3,3	1		1
	1,4	0		-1.02E-32
	2,4	0		-2.78E-17
	3,4	1		1
	1,5	1		1
	2,5	0		1.15E-16
	3,5	0		-2.47E-32
y(i)	1	1		1
	2	0		-2.78E-17
	3	1		1
run time (sec)		0.435921		33.4907

In Table 6.6. it is seen that results are the same for both functions but run time of "fmincon" function is longer than "bintprog".

7. CONCLUSIONS

In this study a time optimization is done for locating Emergency Response Stations. Two different approaches are used for weighing the importance of cells.

Two solutions for accident probability based and accident risk based, give a comparison chance. According to probability based solution, locations of stations at Karabiga, İstanbul and Yalova do not change as number of station increased from 3 to 7. When accident probability data over Marmara Sea is analyzed, it is observed that there are some peaks at Figure 6.1. It is understood that peak values have high effect on the locations of Emergency Response Stations. In risk based solution, locations of stations are changing as the numbers of stations are increased. This can be predicted result, because of accident risk data over Marmara Sea. In Figure 6.2. accident risk data is analyzed and standard deviation is very small so time weighing of cells is very small.

Using wind and current conditions with their magnitude and directional probabilities, and optimizing according to moving oil spill make the project more realistic. But this process can be progressed by using vector averaging techniques.

For a bigger sea, run time may take very long time. Changing resolution can be a solution and another solution can be using heuristic solution algorithms for selecting the optimum combination of stations.

As a future work, optimization according to cost can be done. It will be good for calculating the cost of an accident and cleanup process. Also number of ERS can be decided according to cost optimization.

Another future work, will be use heuristic solutions can be used for faster solutions. Also in this study ERS are assumed as uncapacitated facilities. After some work capacity of facilities can be decided and location of facilities should be re-arranged.

APPENDIX A: SOURCE CODES

A.1. Probability Based Time Calculations

```
%Master Theisis
%Accidient recover analysis for Marmara Sea
clear all;
close all;

%accident probability for each cell
accident=xlsread('accident.xls');
prob_cell=accident(:,3)/(sum(accident(:,3)));      %normalizing the
probability vector


%distance between cells and stations
lngk=cos(pi/180*40);
lngl=111*lngk; %distance between longitudes at 40N
current=xlsread('current.xls');
long=current(:,3);             %longitudes of the cells
latd=current(:,4);            %latitudes of the cells
station=xlsread('station.xls');  %coordinates of stations
st_long=station(:,1);       %long of stations
st_latd=station(:,2);       %latd of stations

for k=1:length(station)'                                 %loop for stations
    for i=1:length(current)'                             %loop for cells
        dx(k,i)=-1*((st_long(k)-long(i))*lngl);          %loop for finding
longitudal distance between station and cell
        dy(k,i)=-1*((st_latd(k)-latd(i))*111);           %loop for finding
latitude distance between station and cell
        d_t(k,i)=sqrt(dx(k,i)^2+dy(k,i)^2)/45;

    end
end

u=sum(d_t'); %sum of the distances of stations to the cells

%wind statistics  (1m/s=3.6km/h)
n(1)=2776;   %N direction blow days
s(1)=2.3*3.6;    %N direction wind speed avarage
n(2)=6289;   %NNE
s(2)=2.9*3.6;    %NNE
n(3)=4816;
s(3)=2.9*3.6;
n(4)=3204;
s(4)=2.8*3.6;
n(5)=1243;
s(5)=2.3*3.6;
n(6)=865;
```

```
s(6)=2.1*3.6;
n(7)=514;
s(7)=1.7*3.6;
n(8)=805;
s(8)=1.9*3.6;
n(9)=1141;
s(9)=2.2*3.6;
n(10)=2117;
s(10)=3.0*3.6;
n(11)=1501;
s(11)=2.7*3.6;
n(12)=1442;
s(12)=2.5*3.6;
n(13)=809;
s(13)=2.5*3.6;
n(14)=786;
s(14)=2.2*3.6;
n(15)=1139;
s(15)=2.1*3.6;
n(16)=1980;
s(16)=2.5*3.6;

total_n=sum(n');   %number of wind blows in a day
for l=1:16
    prob_wind(l)=n(l)/total_n;       %probabaility of wind blowing from
each direction
end

%wind speeds in x & y directions

for l=1:16
    w_s_x(l)=-1*s(l)*sin((pi/8)*(l-1));   %x component of wind speed
    w_s_y(l)=-1*s(l)*cos((pi/8)*(l-1));   %y component of wind speed
end



%currents at the Marmara Sea
current_x=current(:,1).*sin(current(:,2)/180*pi)*3.6; %current in East-West
direction   (West Direction taken as positive)
current_y=current(:,1).*cos(current(:,2)/180*pi)*3.6;    %current in North-
south Direction  (South Direction taken as positive)

%Spilling of oil at the cells due to wind and current in East-West
direction

for i=1:length(current)'
        for l=1:16
            o_s_x(i,l)=0.03*w_s_x(l)+current_x(i) ;       %i is for the
cell number and l is for wind direction
        end
end
% loop for finding the oil spill speed of petrolium in east-west direction
```

```
for i=1:length(current)'
        for l=1:16
            o_s_y(i,l)=0.03*w_s_y(l)+current_y(i);
        end
end

%calculating time for arriving to the cell and from cell to spill location
boat_speed=18 ; %boat speed in km/h



  for k=1:length(station)'                                %loop for
stations
    for i=1:length(current)'                             %loop for cells
        for l=1:16
            c_t_x(k,i)=dx(k,i)/boat_speed;   %arriving time to cell in x
coordinates
            c_t_y(k,i)=dy(k,i)/boat_speed;   %arriving time to cell in y
coordinates
            c_t(k,i)=sqrt(c_t_x(k,i)^2+c_t_y(k,i)^2);     %travel time to
the cell
            o_t_x=(c_t(k,i)*o_s_x(i,l)/(boat_speed-o_s_x(i,l)));   %time
neccessary to reach the spill in x direction
            o_t_y=c_t(k,i)*o_s_y(i,l)/(boat_speed-o_s_y(i,l));   %time
neccessary to reach the spill in y direction
            t_x=c_t_x(k,i)+o_t_x;                                    %total
time for x coordinate
            t_y=c_t_y(k,i)+o_t_y;                                    %total
time for y coordinate
            t(k,i,l)=sqrt(t_x^2+t_y^2);                    %time for
arriving at i,j cell from (k)th station as l wind direction

       end
    end
  end


b=0;
bb=0;
for l=1:16
    b=t(:,:,l); %gives the arrival time for the corresponding wind
direction
    mid_real_time=b+bb;
    bb=b;
end
real_time=sum(mid_real_time');


%mutliplication of wind and accident probabilities with arrival times

for k=1:length(station)'                                %loop for stations
    for i=1:length(current)'                             %loop for cells
            for l=1:16
```

```
                p_arrival_time(k,i,l)=t(k,i,l)*prob_cell(i)*prob_wind(l);
%mutliying probabilities with arrival time for North Stations

        end
    end
end

w_p_arrival_time=zeros(length(station)',length(current)');   %total wind
probabilistic arrival time
w_p_a_t=0;
for l=1:16
    w_p_arrival_time(:,:)=w_p_a_t+p_arrival_time(:,:,l);   %for adding up
of different wind probability arrival time
    w_p_a_t=w_p_arrival_time;
end



                                    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%ESTIMATED ARRIVAL TIME FOR N STATION

number_of_station=2;                            %number of stations
station_matrix=combnk(1:length(station)',number_of_station); %combination
for n station installation

[ee,ff]=size(station_matrix);  %dimensions of station matrix

for i=1:length(current)'                %loop for cell
    for e=1:ee     %loop for groups (row) of station matrix

        a_of_n_station(e,i)=min(w_p_arrival_time(station_matrix(e,:),i));
%arrival for group of n station for 1 cell


    end
end

estimated_arrival_time_for_n_station=sum(a_of_n_station,2);

[min_estimated_time_n_station,i_min_estimated_n_station]=min(estimated_arri
val_time_for_n_station);   %optimum places of stations for min. estimated
time

min_est_time_stations=station_matrix(i_min_estimated_n_station,:);
%optimum station numbers for min. estimated time

figure   %01
scatter(st_long,st_latd); hold
scatter(st_long(min_est_time_stations(:)),st_latd(min_est_time_stations(:))
,'filled','r');  %plot for optimum stations
```

```
        %for worst case scenario take wind probability, which associate
with
        %the longest arrival time to the cell, as 1. do not make any
        %calculations according to other wind directions
max_p_arrival_time=zeros(length(station),length(current)); %max_p_arrival
time empty matrix
max_p_time=zeros(length(station),length(current));

for k=1:length(station)'
    for i=1:length(current)'
        [m_p_a_t,m_p_t]=max(p_arrival_time(k,i,:));
        max_p_arrival_time(k,i)=m_p_a_t;                %maximum arrival
time for worst wind spilling case
        max_p_time(k,i)=m_p_t;                          %associated wind
direction for worst spilling case

max_w_arrival_time(k,i)=max_p_arrival_time(k,i)/prob_wind(max_p_time(k,i))
;         %worst case wind probability taken as 1
    end
end



for i=1:length(current)'                %loop for cell
    for e=1:ee     %loop for groups (row) of station matrix


max_wind_a_of_n_station(e,i)=min(max_w_arrival_time(station_matrix(e,:),i))
; %maximum arrival for group of n station for 1 cell



    end
end

max_wind_arrival_time_for_n_station=sum(max_wind_a_of_n_station,2); %worst
case for maximum arrival time
%wind probability taken as 1 and the maximum travel time station to cell
%taken as main parameter


[min_max_wind_time_n_station,i_min_max_wind_n_station]=min(max_wind_arrival
_time_for_n_station);   %optimum places of stations for min. estimated time

min_max_wind_time_stations=station_matrix(i_min_max_wind_n_station,:);
%optimum station numbers for min. estimated time

figure    %02
scatter(st_long,st_latd); hold
scatter(st_long(min_max_wind_time_stations(:)),st_latd(min_max_wind_time_st
ations(:)),'filled','r');          %plot for optimum stations
```

```
e_time=sum(w_p_arrival_time,2);
figure   %03
plot(u);

%plot (prob_wind);

figure   %04
subplot(3,1,1), plot(e_time);
subplot(3,1,2), plot(real_time);
subplot(3,1,3),plot(u);

figure   %05

for aaa=1:length(station)'
st_time(aaa,aaa)=e_time(aaa);
end
scatter3(accident(:,1),accident(:,2),accident(:,3),120,accident(:,3),'s','f
illed');


figure   %06
plot3(st_long,st_latd,st_time,'o');

quiver(current(:,3),current(:,4),current_x,current_y)%current map
[timemin,imin]=min(e_time);
plot (st_long(imin),st_latd(imin),'xr'); hold
scatter(st_long,st_latd);

figure  %07
quiver(current(:,3),current(:,4),o_s_x(:,2),o_s_y(:,2));   %oil spill model
for NNE wind direction

figure  %08
quiver(current(:,3),current(:,4),o_s_x(:,10),o_s_y(:,10));   %oil spill
model for SSW wind direction

figure   %09
plot3(accident(:,2),accident(:,3),accident(:,1),'o');
figure  %10
scatter3(accident(:,1),accident(:,2),accident(:,3),120,accident(:,3),'fille
d','s');
figure   %11
scatter3(st_long,st_latd,e_time,40,e_time,'filled');
ttime=e_time;
a_time(:,1)=ttime(:,1);
a_time(:,2)=station(:,1);
a_time(:,3)=station(:,2);   %creates a matrix that contains weighted time,
latitude and longitude of stations
s_time=sortrows(a_time);    %sorted matrix according to weighted arrival
time

figure   %12
```

```
plot(e_time)
xlabel('station no')
ylabel('expected arrival time (hrs)')

figure  %13
scatter3(st_long,st_latd,e_time,40,e_time,'filled'); hold

for kst=1:length(station)'

text(s_time(kst,2),s_time(kst,3),s_time(kst,3),int2str(kst),'FontSize',12);
hold
end

text(s_time(1,2),s_time(1,3),s_time(1,3),'1','FontSize',18);hold
text(s_time(2,2),s_time(2,3),s_time(2,3),'2','FontSize',18);hold
text(s_time(3,2),s_time(3,3),s_time(3,3),'3','FontSize',18);

ii=1:length(prob_cell);
m_prob=mean(prob_cell); %mean of accident probability
mm_prob(ii)=m_prob;
figure %14
stem(prob_cell (ii,1)); hold
plot(mm_prob(:),'- r');
std_prob=std(prob_cell);        %standard deviation of accident probability

wind_direction=[0 22.5 45 67.5 90 102.5 135 157.5 180 202.5 225 247.5 270
292.5 315 337.5 360];
wind_direction=wind_direction*pi/180;
wind_prob=100*prob_wind;
wind_prob(17)=100*prob_wind(1);
figure %15 wind probability rose
polar(wind_direction,wind_prob);

o_s=(o_s_x.^2+o_s_y.^2).^0.5; %oil spill velocity
```

A.2. Risk Based Time Calculations

```
%Master Theisis
%Accidient recover analysis for Marmara Sea
clear all;
close all;

%accident risk for each cell
accident=xlsread('accident.xls');
prob_cell=accident(:,3)/(sum(accident(:,3)));      %normalizing the
probability vector
risk=accident(:,4)/(sum(accident(:,4)));            %normalizing the risk
vector


%distance between cells and stations
lngk=cos(pi/180*40);
lngl=111*lngk; %distance between longitudes at 40N
current=xlsread('current.xls');
long=current(:,3);             %longitudes of the cells
latd=current(:,4);            %latitudes of the cells
station=xlsread('station.xls');  %coordinates of stations
st_long=station(:,1);       %long of stations
st_latd=station(:,2);       %latd of stations

for k=1:length(station)'                                 %loop for stations
    for i=1:length(current)'                             %loop for cells
        dx(k,i)=-1*((st_long(k)-long(i))*lngl);          %loop for finding
longitudal distance between station and cell
        dy(k,i)=-1*((st_latd(k)-latd(i))*111);           %loop for finding
latitude distance between station and cell
        d_t(k,i)=sqrt(dx(k,i)^2+dy(k,i)^2)/45;

    end
end

u=sum(d_t'); %sum of the distances of stations to the cells

%wind statistics  (1m/s=3.6km/h)
n(1)=2776;   %N direction blow days
s(1)=2.3*3.6;    %N direction wind speed avarage
n(2)=6289;   %NNE
s(2)=2.9*3.6;    %NNE
n(3)=4816;
s(3)=2.9*3.6;
n(4)=3204;
s(4)=2.8*3.6;
n(5)=1243;
s(5)=2.3*3.6;
n(6)=865;
s(6)=2.1*3.6;
n(7)=514;
s(7)=1.7*3.6;
n(8)=805;
```

```
s(8)=1.9*3.6;
n(9)=1141;
s(9)=2.2*3.6;
n(10)=2117;
s(10)=3.0*3.6;
n(11)=1501;
s(11)=2.7*3.6;
n(12)=1442;
s(12)=2.5*3.6;
n(13)=809;
s(13)=2.5*3.6;
n(14)=786;
s(14)=2.2*3.6;
n(15)=1139;
s(15)=2.1*3.6;
n(16)=1980;
s(16)=2.5*3.6;

total_n=sum(n');   %number of wind blows in a day
for l=1:16
    prob_wind(l)=n(l)/total_n;       %probabaility of wind blowing from
each direction
end

%wind speeds in x & y directions

for l=1:16
    w_s_x(l)=-1*s(l)*sin((pi/8)*(l-1));   %x component of wind speed
    w_s_y(l)=-1*s(l)*cos((pi/8)*(l-1));   %y component of wind speed
end



%currents at the Marmara Sea
current_x=current(:,1).*sin(current(:,2)/180*pi)*3.6; %current in East-West
direction   (West Direction taken as positive)
current_y=current(:,1).*cos(current(:,2)/180*pi)*3.6;    %current in North-
south Direction  (South Direction taken as positive)

%Spilling of oil at the cells due to wind and current in East-West
direction

for i=1:length(current)'
        for l=1:16
            o_s_x(i,l)=0.03*w_s_x(l)+current_x(i) ;       %i is for the
cell number and l is for wind direction
        end
end
% loop for finding the oil spill speed of petrolium in east-west direction

for i=1:length(current)'
        for l=1:16
            o_s_y(i,l)=0.03*w_s_y(l)+current_y(i);
        end
```

```
end

%calculating time for arriving to the cell and from cell to spill location
boat_speed=18 ; %boat speed in km/h



  for k=1:length(station)'                                %loop for
stations
    for i=1:length(current)'                              %loop for cells
        for l=1:16
            c_t_x(k,i)=dx(k,i)/boat_speed;   %arriving time to cell in x
coordinates
            c_t_y(k,i)=dy(k,i)/boat_speed;   %arriving time to cell in y
coordinates
            c_t(k,i)=sqrt(c_t_x(k,i)^2+c_t_y(k,i)^2);     %travel time to
the cell
            o_t_x=(c_t(k,i)*o_s_x(i,l)/(boat_speed-o_s_x(i,l)));   %time
neccessary to reach the spill in x direction
            o_t_y=c_t(k,i)*o_s_y(i,l)/(boat_speed-o_s_y(i,l));   %time
neccessary to reach the spill in y direction
            t_x=c_t_x(k,i)+o_t_x;                                   %total
time for x coordinate
            t_y=c_t_y(k,i)+o_t_y;                                   %total
time for y coordinate
            t(k,i,l)=sqrt(t_x^2+t_y^2);                       %time for
arriving at i,j cell from (k)th station as l wind direction

       end
    end
  end



b=0;
bb=0;
for l=1:16
    b=t(:,:,l); %gives the arrival time for the corresponding wind
direction
    mid_real_time=b+bb;
    bb=b;
end
real_time=sum(mid_real_time');



%mutliplication of wind and accident probabilities with arrival times

for k=1:length(station)'                                %loop for stations
    for i=1:length(current)'                              %loop for cells
            for l=1:16
                p_arrival_time(k,i,l)=t(k,i,l)*risk(i)*prob_wind(l);
%mutliying probabilities with arrival time for North Stations

        end
```

```
    end
end

w_p_arrival_time=zeros(length(station)',length(current)');   %total wind
probabilistic arrival time
w_p_a_t=0;
for l=1:16
    w_p_arrival_time(:,:)=w_p_a_t+p_arrival_time(:,:,l);   %for adding up
of different wind probability arrival time
    w_p_a_t=w_p_arrival_time;
end



                                    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%ESTIMATED ARRIVAL TIME FOR N STATION

number_of_station=2;                            %number of stations
station_matrix=combnk(1:length(station)',number_of_station); %combination
for n station installation

[ee,ff]=size(station_matrix);  %dimensions of station matrix

for i=1:length(current)'                %loop for cell
    for e=1:ee     %loop for groups (row) of station matrix

        a_of_n_station(e,i)=min(w_p_arrival_time(station_matrix(e,:),i));
%arrival for group of n station for 1 cell


    end
end

estimated_arrival_time_for_n_station=sum(a_of_n_station,2);

[min_estimated_time_n_station,i_min_estimated_n_station]=min(estimated_arri
val_time_for_n_station);   %optimum places of stations for min. estimated
time

min_est_time_stations=station_matrix(i_min_estimated_n_station,:);
%optimum station numbers for min. estimated time

figure   %01
scatter(st_long,st_latd); hold
scatter(st_long(min_est_time_stations(:)),st_latd(min_est_time_stations(:))
,'filled','r');  %plot for optimum stations

        %for worst case scenario take wind probability, which associate
with
        %the longest arrival time to the cell, as 1. do not make any
        %calculations according to other wind directions
max_p_arrival_time=zeros(length(station),length(current)); %max_p_arrival
time empty matrix
```

```
max_p_time=zeros(length(station),length(current));

for k=1:length(station)'
    for i=1:length(current)'
        [m_p_a_t,m_p_t]=max(p_arrival_time(k,i,:));
        max_p_arrival_time(k,i)=m_p_a_t;                  %maximum arrival
time for worst wind spilling case
        max_p_time(k,i)=m_p_t;                            %associated wind
direction for worst spilling case

max_w_arrival_time(k,i)=max_p_arrival_time(k,i)/prob_wind(max_p_time(k,i))
;         %worst case wind probability taken as 1
    end
end



for i=1:length(current)'                %loop for cell
    for e=1:ee     %loop for groups (row) of station matrix


max_wind_a_of_n_station(e,i)=min(max_w_arrival_time(station_matrix(e,:),i))
; %maximum arrival for group of n station for 1 cell


    end
end

max_wind_arrival_time_for_n_station=sum(max_wind_a_of_n_station,2); %worst
case for maximum arrival time
%wind probability taken as 1 and the maximum travel time station to cell
%taken as main parameter


[min_max_wind_time_n_station,i_min_max_wind_n_station]=min(max_wind_arrival
_time_for_n_station);   %optimum places of stations for min. estimated time

min_max_wind_time_stations=station_matrix(i_min_max_wind_n_station,:);
%optimum station numbers for min. estimated time

figure    %02
scatter(st_long,st_latd); hold
scatter(st_long(min_max_wind_time_stations(:)),st_latd(min_max_wind_time_st
ations(:)),'filled','r');          %plot for optimum stations




e_time=sum(w_p_arrival_time,2);
figure   %03
plot(u);
```

```
%plot (prob_wind);

figure   %04
subplot(3,1,1), plot(e_time);
subplot(3,1,2), plot(real_time);
subplot(3,1,3),plot(u);

figure   %05

for aaa=1:length(station)'
st_time(aaa,aaa)=e_time(aaa);
end
scatter3(accident(:,1),accident(:,2),risk(:),120,risk(:),'s','filled');


figure   %06
plot3(st_long,st_latd,st_time,'o');

quiver(current(:,3),current(:,4),current_x,current_y)%current map
[timemin,imin]=min(e_time);
plot (st_long(imin),st_latd(imin),'xr'); hold
scatter(st_long,st_latd);

figure  %07
quiver(current(:,3),current(:,4),o_s_x(:,2),o_s_y(:,2));   %oil spill model
for NNE wind direction

figure  %08
quiver(current(:,3),current(:,4),o_s_x(:,10),o_s_y(:,10));   %oil spill
model for SSW wind direction

figure   %09
plot3(accident(:,2),risk,accident(:,1),'o');
figure  %10
scatter3(accident(:,1),accident(:,2),risk(:),120,risk(:),'filled','s');
figure   %11
scatter3(st_long,st_latd,e_time,40,e_time,'filled');
ttime=e_time;
a_time(:,1)=ttime(:,1);
a_time(:,2)=station(:,1);
a_time(:,3)=station(:,2);   %creates a matrix that contains weighted time,
latitude and longitude of stations
s_time=sortrows(a_time);    %sorted matrix according to weighted arrival
time

figure   %12
plot(e_time)
xlabel('station no')
ylabel('expected arrival time (hrs)')

figure  %13
scatter3(st_long,st_latd,e_time,40,e_time,'filled'); hold
```

```
for kst=1:length(station)'

text(s_time(kst,2),s_time(kst,3),s_time(kst,3),int2str(kst),'FontSize',12);
hold
end

text(s_time(1,2),s_time(1,3),s_time(1,3),'1','FontSize',18);hold
text(s_time(2,2),s_time(2,3),s_time(2,3),'2','FontSize',18);hold
text(s_time(3,2),s_time(3,3),s_time(3,3),'3','FontSize',18);

ii=1:length(risk);
m_risk=mean(risk); %mean of accident probability
mm_risk(ii)=m_risk;
figure %14
stem(risk (ii,1)); hold
plot(mm_risk(:),'- r');
std_risk=std(risk);             %standard deviation of risk
```

A.3. Probability Based Allocation

```
%Location allocation with Binary Integer Programming
clear all
close all

p=2; %number of stations that will be located

distance=xlsread('distance1.xls');

[i,j]=size(distance);       %i number of station j number of cell

onesvector=ones(1,i);

Aeq=blkdiag(onesvector,onesvector,onesvector,onesvector,onesvector,onesvect
or,onesvector,onesvector,onesvector,onesvector); %
%constrain for one and one response for every cell

Aeq(1:j,(i*j)+1:(i*j)+i)=zeros(j,i);
Aeq(j+1,(i*j)+1:(i*j)+i)=ones(1,i);
beq=ones(j,1);
beq(j+1,1)=p;

%A=Aeq;
%b=beq;
dist=reshape(distance,1,numel(distance));

dist(1,j*i+1:j*i+i)=zeros(1,i);

I=eye([i*j,i*j+i]);             %for yi>=xi constrain

k=i*j+1:i*j+i;
l=1:i*j;
m=i*j;

ip=-1*repmat(eye([i,i]),j,1);
A=eye(i*j);
A(l,k)=ip(:,:);
b=zeros(i*j,1);


%A(1:j,(i*j)+1:(i*j)+5)=zeros(j,5);



%A((j+l):(j+m),:)=I(:,:);

x=bintprog(dist,A,b,Aeq,beq);
```

A.4. Risk Based Allocation

```
%Location allocation with Binary Integer Programming
clear all
close all

p=2; %number of stations that will be located

distance=xlsread('distance1.xls');

[i,j]=size(distance);       %i number of station j number of cell

onesvector=ones(1,i);
m=i*j;

for jj=1:j
   Aeq(jj, :) = [zeros(1, i*(jj-1)) ones(1,i) zeros(1, m-i*jj)];
end


%constrain for one and one response for every cell

Aeq(1:j,(i*j)+1:(i*j)+i)=zeros(j,i);
Aeq(j+1,(i*j)+1:(i*j)+i)=ones(1,i);
beq=ones(j,1);
beq(j+1,1)=p;

%A=Aeq;
%b=beq;
dist=reshape(distance,1,numel(distance));

dist(1,j*i+1:j*i+i)=zeros(1,i);

I=eye([i*j,i*j+i]);             %for yi>=xi constrain

k=i*j+1:i*j+i;
l=1:i*j;


ip=-1*repmat(eye([i,i]),j,1);
A=eye(i*j);
A(l,k)=ip(:,:);
b=zeros(i*j,1);


%A(1:j,(i*j)+1:(i*j)+5)=zeros(j,5);



%A((j+1):(j+m),:)=I(:,:);
tic                     %starts stopwatch
```

```
x=bintprog(dist,A,b,Aeq,beq);
toc                        %ends stopwatch
```

A.5. Run Time Comparision

```
clear all
close all

p=3; %number of stations that will be located
reduction=4;
distance_f=xlsread('distance_prob.xls');

[m,n]=size(distance_f);       %m number of station n number of cell

nn=1:reduction:n;
distance_r(:,:)=distance_f(:,nn);

mm=1:reduction:m;
distance(:,:)=distance_r(mm,:);

[i,j]=size(distance);       %m number of station n number of cell

onesvector=ones(1,i);
mn=i*j;

for jj=1:j
   Aeq(jj, :) = [zeros(1, i*(jj-1)) ones(1,i) zeros(1, mn-i*jj)];
end


%constrain for one and one response for every cell

Aeq(1:j,(i*j)+1:(i*j)+i)=zeros(j,i);
Aeq(j+1,(i*j)+1:(i*j)+i)=ones(1,i);
beq=ones(j,1);
beq(j+1,1)=p;

%A=Aeq;
%b=beq;
dist=reshape(distance,1,numel(distance));

dist(1,j*i+1:j*i+i)=zeros(1,i);

I=eye([i*j,i*j+i]);             %for yi>=xi constrain

k=i*j+1:i*j+i;
l=1:i*j;


ip=-1*repmat(eye([i,i]),j,1);
A=eye(i*j);
A(l,k)=ip(:,:);
b=zeros(i*j,1);
```

```
%A(1:j,(i*j)+1:(i*j)+5)=zeros(j,5);



%A((j+1):(j+m),:)=I(:,:);
tic                         %starts stopwatch
x=bintprog(dist,A,b,Aeq,beq);
toc                         %ends stopwatch
```

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