# Risk and Vulnerability Analysis in the Gulf of Finland

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**Key words**: Risk, Vulnerability Analysis, Automatic Identification System (A.I.S.), shipping Accidents, Vessel Traffic Service (V.T.S.)

## SUMMARY

In 1994, the biggest catastrophe ever in the Gulf of Finland caused the deaths of more than eight hundred people in a major shipping accident. This major accident and the increase in the sea traffic between Helsinki and Tallinn, which crosses waterways going into and out of St. Petersburg, led to the study of the risks and vulnerability of shipping traffic in many research studies. In this paper, the authors aim to present risk and vulnerability models in the Gulf of Finland based on data from the Automatic Identification System. The risk model uses the accident probability density and population density model for the analysis, whereas the vulnerability analysis uses data based on the A.I.S. The risk model anticipates the location of future accidents on the basis of accident history information and the probability of an accident occurring. Therefore, it can be used to define the areas where people may be affected by shipping accidents. The vulnerability model can be used to detect ships that cannot be reached by either the rescue units or nearby ships in the traffic flow at the given time. The vulnerability analysis chart can be used to predict the future position of ships in the traffic flow and the capability of the rescue units. The outcome of both analyses is useful information for the coastguard unit, which can assist them in their work, for example, to assist them in setting up patrols for the observation of ships that may be at risk. This study can be taken as a preliminary study for building a real-time coastguard system. Some factors were left out of this study, for instance, the weather conditions and the season. These factors can be added to a subsequent study to improve the quality of the model and produce more realistic results.

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## 1. INTRODUCTION

The search and rescue (SAR) issue is one of the most important topics in sea-related studies. Search and rescue activities at sea are different from onshore ones. The spatial and temporal scales are different. Distances are longer and speeds are lower than on the shore. GIS applications can be used to render and present a real-time situation picture of a crisis. Such applications can also be used in maritime rescue activities, giving a real-time situation picture of the traffic vulnerability or presenting risk analysis results. GIS can be utilised throughout the entire crisis management process (e.g. Cova, 1999; Seppänen, 2009), from mitigation and preparedness to the response and recovery phases. Risk and vulnerability analyses belong to the mitigation and preparedness phases. Risk analysis can help in reducing the amount of accidents; vulnerability analysis supports risk analysis for mitigation, as well as giving valuable information for preparedness purposes.

In the Gulf of Finland, the main traffic is an east-west flow of tankers and cargo vessels, which are travelling to or from Russia. Both these waterways are crossed by passenger ferries sailing from north to south between Helsinki, Finland and Tallinn, Estonia. The main danger lies in this crossing area. Since the catastrophe of the MS Estonia in 1994, search and rescue at sea has been the subject of many studies. Disasters cannot always be avoided but they can be prevented and anticipated. This study attempts to develop two approaches to help decision making for search and rescue operations. The first approach is a risk analysis, which is able to predict the location of risky areas according to the current traffic and previous accidents. The second is a vulnerability analysis based on the accessibility of the sea. Both analyses use A.I.S. (Automatic Identification System) data to obtain shipping information.

This study is separated into different parts. First, a literature study gives definitions of the concepts used in this work and defines the methods used to process both the risk and vulnerability analysis of the sea. Next, an explanation is given of the methods used to develop the models and how they are processed. Some results given by these analyses are described and discussed. Finally, the suggestions from the potential users, the Finnish coastguards, are reviewed in order to try to define problems for further studies. This work can also be used to assist search and rescue activities in the Gulf of Finland by giving a real-time situation picture of the dangers and their consequences. This awareness could give the coastguards tools to be more reactive and save time and people more easily.

## 2. DATA AND MODEL ANALYSIS

### 2.1 A.I.S. Data

It is not possible to get data from every ship at sea. The A.I.S. provides a lot of data but only on ships that are defined by the I.M.O. (International Maritime Organisation) regulations (I.M.O., 1998). Smaller ships do not send any information and their behaviour is erratic; therefore these kinds of ships are ignored. The A.I.S. data in this study are provided by F.M.A. (Finnish Maritime Administration); the data were collected on 3 April 2009. The available information about ships is:

| |
|---|
| Time stamp of the receipt of the message |
| Position of the ship |
| Speed Over the Ground (SOG) |
| Course Over the Ground (COG) |
| Draught |
| Ship type |
| Navigation status |

**Table 1: Available data in the received A.I.S. dataset**

To use A.I.S. data in GIS, some modifications were made to the file layout. First, the data were clipped into the study area. Next, the date and time were set to a compatible format for ArcGIS. Finally, the name corresponding to the code for the navigational status (COMSAR, 2008) and the ship type (IALA, 2004), (see Tables 11 and 12) were added. The data were imported and processed in ArcGIS.

### 2.2 Accident history

No source was able to supply this study with accident history data. Therefore, the work of Kujala et al. (2009) was used to define accidents in the area being studied. Figure 1 presents the accident history used in this study; the wreck symbols represent the position of an accident. These accidents were positioned according to the accident history data based on collisions, groundings, and others, and therefore, the positions are not accurate. But this study is more about the way to process the data than the results themselves.

**Figure 1: Accident history defined for this study**

## 2.3 Rescue Unit Data

The rescue units' data are collected in a different format because they are from different sources. Coastguards receive the GPS positions from their ships, but the rescue ships can also be tracked through the A.I.S. Because of this, random data have been used for rescue ship positions in this study.

## 2.4 Models

### 2.4.1 Risk

Virrantaus (2009) has given a definition review of basic terms in Risk Analysis and Crisis Management. There are several definitions of a risk. According to Godschalk (1999), a risk is the probability of a hazard occurring during a particular time period. In this study, the mathematical form given by Smith (1996) has been used (see Equation 1). In the equation *P(E)* describes the occurrence probability of the event and *C(e)* describes the cost of the occurrence.

$$R(e) = P(e) \cdot C(e)$$

**Equation 1: Risk function expression**

This mathematical formulation joins the definition given by Ayyub (2003): the risk is the product of the probability of the occurrence and the severity of the impact of the occurrence of the event. The cost is regarded here as the impact severity of the occurrence. Risk analysis is important in crisis management because risks create dangers, and dangers create accidents. If the risks are taken into consideration, accidents can be prevented. In this study, a risk model was developed. This model is the product of two models; a probability model and a cost model. Risk, according to this definition, is based on statistics about accidents. In order to calculate the risk, one has to have information about previous similar accidents, both the circumstances in which they occurred and the consequences of the accident.

The Maritime Activity and Risk Investigation Network (MARIN), a Canadian research group, set up a system to analyse risks near the Canadian coast (MARIN, 2009). They developed a theory about accident distribution. Accidents are not randomly distributed around the sea but there are some spots where accidents occur more often. It could be because of a danger in this area, a rock, or a difficult approach in bad weather conditions. So the accident probability density is not uniform throughout the sea area. The probability increases close to these hot spots. Therefore, it is reasonable to set SAR units to patrol close to these areas.

Ylitalo et al. (2008) studied how to compute the probability of the occurrence of groundings and ship-to-ship collisions. They selected several areas in the Gulf of Finland using two different mathematical models. The probabilities were computed for the winter and the summer period; they also calculated the same probabilities according to an increase in traffic as a result of a new terminal opening around 2015 in Russia.

### 2.4.2 Vulnerability

The vulnerability of a system can be defined as its susceptibility to injury or damage from hazard (Godshalk, 1991). This potential weakness was explained by Sarewitz et al. (2003) as a set of characteristics of the system that create the potential for harm. Vulnerability is not based on probability and statistics. Vulnerability is more a characteristic of the "underlying system", the weakness or resiliency of the system. Vulnerability affects both parts of the risk formula, the probability and the consequences. Cova (1999) suggested a formulation for the vulnerability according to the risk (see Equation 2). In the equation *H(e)* represents the function of the hazard elements and *V(e)* represents the function of the vulnerability elements. The result of the hazard and vulnerability functions is the risk function *R(e)*.

$$R(e) = R(H(e), V(e))$$

**Equation 2: Risk according to Hazard and Vulnerability**

Deltamarin (2006) performed a study about rescue capacity in the east of the Gulf of Finland. This study reviewed all the means available to rescue people at sea in the Gulf of Finland. Deltamarin reviewed not only the Finnish equipment but also the Estonian and Russian resources as well. A chart of the rescue access capability in the Gulf is presented in Figure 2.

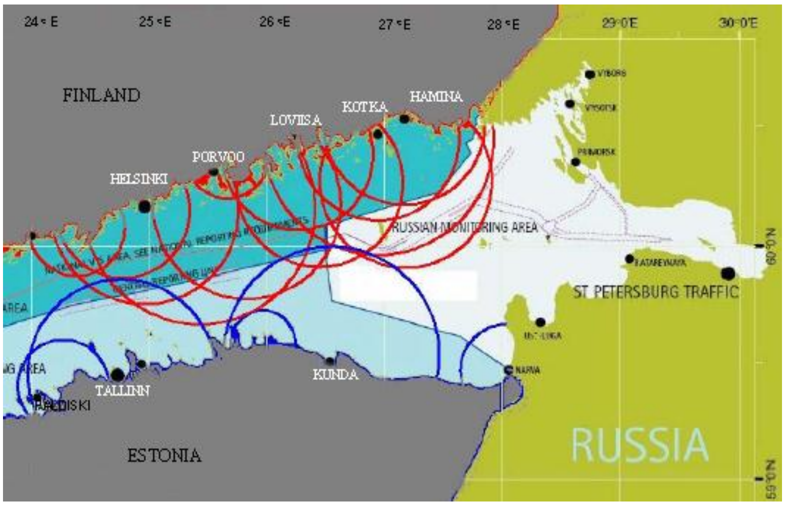


**Figure 2: Estonian and Finnish search and rescue capability (bad weather conditions)**

Cova (1999) explained that the vulnerability (V) is a variable, like the hazard (H), in the risk function (R), as in crisis management risk and vulnerability are independent (Sarewitz et al., 2003). It is valuable to make an analysis of both. A ship that cannot be reached by either the traffic or SAR ships is vulnerable; mutual aid at sea is customary. If a ship has a problem, other ships can reroute to help her. The decision to reroute can be made by the captain, but the coastguards can also ask a ship to reroute to assist. The coastguards own a system that displays a real-time situation picture based on A.I.S. data.

## 3. METHODS

### 3.1 Risk model

To compute a risk model, a probability model is needed. In this study, a model of accident probability density was developed, as shown in Figure 3. This model gives a value of the probability density of accidents in the whole study area.

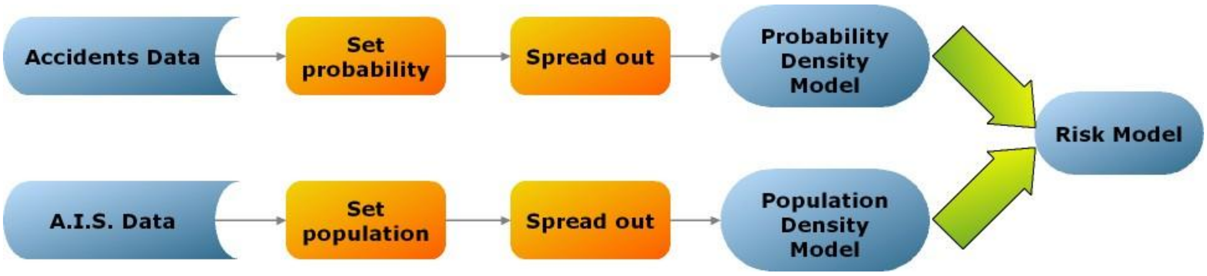


**Figure 3: Risk model creation diagram**

#### 3.1.1 Accident Probability Density Model

As reported by the Maritime Activity and Risk Investigation Network (MARIN), new accidents are likely to occur more often in areas close to previous accidents; the accident probability density model used in this study is based on this assumption (MARIN, 2009). The accident probability density model developed in this study uses the probability of the occurrence of accidents positioned around previous accident events.

Kujala et al. (2009) emphasised that the most frequent accidents in the Gulf of Finland were ship-to-ship collisions and groundings. Therefore, in this study, only ship-to-ship collisions and groundings were retained. Ylitalo et al. (2008) computed the probabilities of the occurrence of groundings and ship-to-ship collisions. For each type of accident the most unfavourable probability was chosen. The probabilities used in the accident probability density model are presented in Table 2.

| | |
|---|---|
| Grounding probability | 2.0e-2 (cases per month) |
| Ship-ship collision probability | 1.6357e-2 (cases per month) |

**Table 2: Probabilities used in the accident probability density model**

Because a ship cannot run aground and hit another ship at the same time, the hypothesis that all accidents are disjunctive was created. In this case, the probability of a new accident is the sum of the grounding probability and the ship-to-ship collision probability, as in Equation 3. P(X) is the probability of parameter X, e.g. P(Grounding) is the grounding probability and P(Collision) is Ship-ship collision probability.

$$P(New) = P(Grounding) + P(Collision) - \overbrace{P(Grounding \cap Collision)}^{0}$$
$$P(New) = P(Grounding) + P(Collision)$$

**Equation 3: Probability of new accident**

Gaussian distributions were used to spread the accident probabilities around each accident position. Then, according to Equation 3, the probabilities can be summed up to give the new accident occurrence probability; therefore all the Gaussian distributions were summed up to give the model.

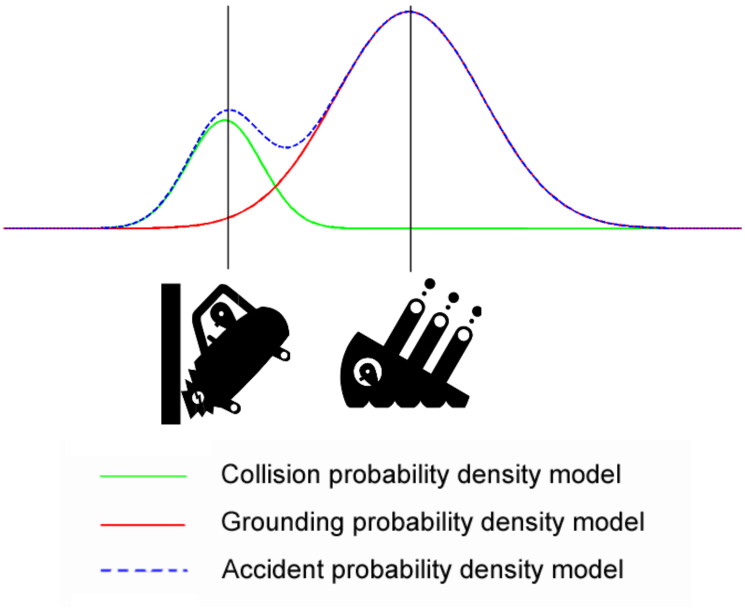


**Figure 4: Explanation of the creation of the probability density**

Figure 4 explains the construction of the accident probability density model. It shows only two accidents: one of each type. Gaussian distributions of probability are drawn around their respective accident positions. Then, to compute the model, all the Gaussian distributions are summed up; it gives the blue function that is the accident probability density model.

### 3.1.2 <u>Onboard Population Density Model</u>

In an SAR operation, the rescue units are only interested in the people to be rescued; therefore the number of people that are on board is the cost, in the risk function. A model of the onboard population density was developed to give a value of the onboard population in the whole study area.

Although the A.I.S. data do not supply any information about the number of people on board, the ship type can be used to estimate the population. According to Sea and Navy (2009), an average population for ferries was selected, as shown in Table 3. Because of the variety of data and the difficulty of finding data about other ship types, the average value was appraised without any support.

| Ship type | Population on board |
|---|---|
| Ferries | 1500 (crew included) |
| High-Speed Craft | 1500 (crew included) |
| Tankers | 25 |
| Cargo vessels | 25 |
| Sailing boats, tugs, etc… | 5 |

**Table 3: Population model of ships carrying A.I.S.**

In order to apply those values to ships that are at sea, the onboard population was spread around the position given by the A.I.S. data. Again, a Gaussian distribution was used to share the population out.

#### 3.1.3 Risk Calculation

The risk value was computed by multiplying both the probability and onboard population values. Figure 5 gives an explanation of the results.

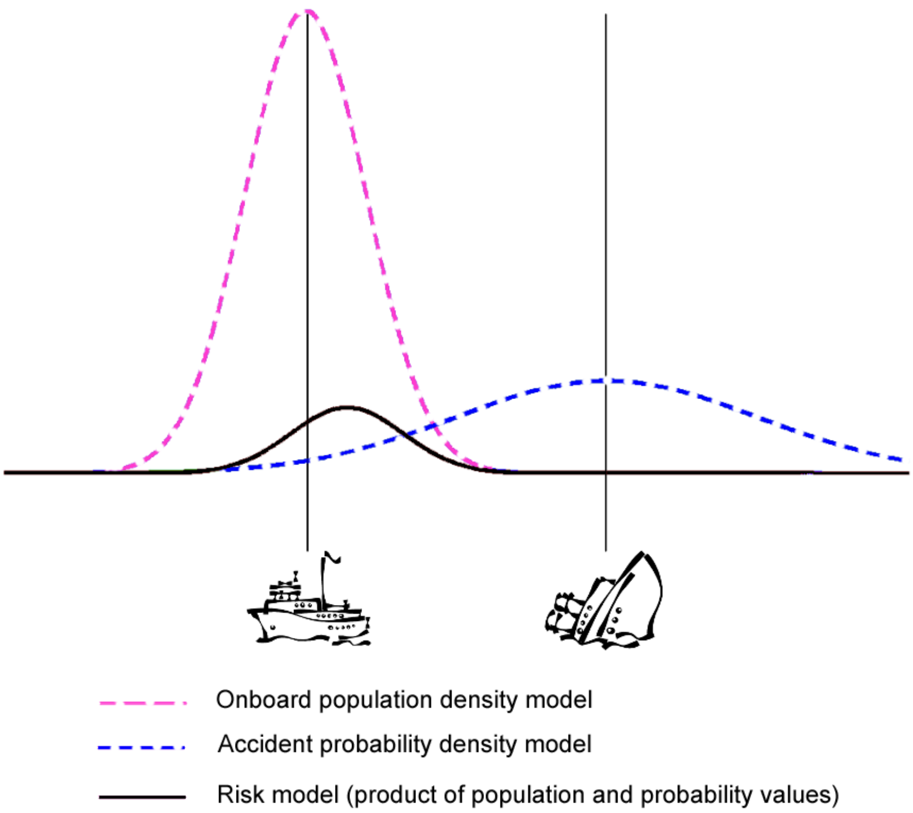


**Figure 5: Explanation of the risk calculation**

The magenta function represents the onboard population density model; the blue function represents the accident probability density model. The black function is the product of the magenta and blue functions and represents the risk model.

### 3.2 Vulnerability Model

The vulnerability analysis was performed by creating buffers around each ship at sea. These buffers describe the area, which is accessible by that ship within a specified time. The buffers were drawn according to the Speed Over the Ground (SOG) given by the A.I.S. data and the direction was a straight line from the ship outwards. In accessibility at sea, direct connections from one place to another were considered, because in most places the sea is open; islands or other obstacles were not taken into account. This vulnerability analysis could help coastguards in their decision making to determine the locations in which ships are "isolated", i.e. in locations at which they cannot be accessed in the required time. These areas can also be called "vulnerable areas of the sea". The construction of the vulnerability model is presented in Figure 6.

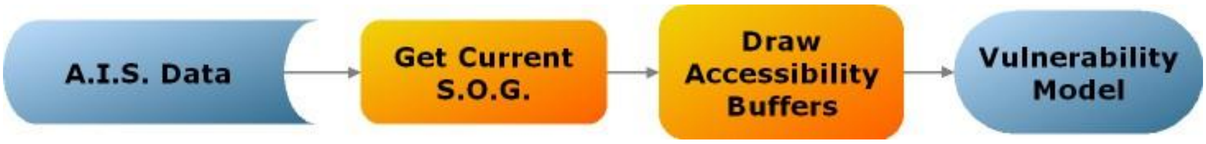


**Figure 6: Vulnerability model creation diagram**

Each ship was surrounded by four circular buffers. Each one displayed the area reachable within a different given time. Basically, 15, 30, 45, and 60 min were chosen. Isolated ships are visible in those buffers; for instance, if a ship is not in any 15 min buffers, she cannot be reached in less than 15 min. With this information SAR units can be sent to fill the gaps, and ships being isolated can be avoided.

## 4. RESULTS

### 4.1 Risk Analysis

As mentioned earlier, the risk analysis is supported by two models, the accident probability density model and the population model.

Figure 7 shows the population model built according to the theory developed in the preceding part, between Helsinki and Tallinn. The black zones represent the high population density area and the white zones represent the low population density area.

The crossing area between Helsinki and Tallinn is represented as the most risky area in the study area. Kujala et al. (2009) found this crossing area to be the area with the highest probability of either a ship-to-ship collision or grounding. This study confirms this result.

Figure 8 is the result of the risk analysis between Helsinki and Tallinn. It shows the current traffic according to the A.I.S. data and a raster giving the value of the risk function. Three colours are chosen; blue for a low-risk area, yellow-white for a medium-risk area, and red for a high-risk area. There are three passenger ferries on the chart, which are close to the accident areas; the risk function is high close to these ships. As a result, if the coastguards decided to set a patrol, they could take this result into consideration and search for the best location for the rescue ship in order to cover all those areas.

**Figure 7: Population density model (left) and accident probability density model (right) between Helsinki and Tallinn.**

**Figure 8: Result of the risk analysis between Helsinki and Tallinn**

## 4.2 Vulnerability Analysis

The vulnerability analysis, as mentioned in an earlier section, is able to act as a guide to detect isolated ships or areas in which they cannot be reached in the required time.

Figure 9 presents the area that can be reached for rescue purposes for all ships that are carrying an A.I.S. in the study area. The times needed to reach them are 15, 30, 45 and 60 min. The isolated ships are easily detectable. For instance, the two ships on the left-hand side of Figure 9 (red rectangle) are sailing to the east and are far from other ships in the traffic flow. They cannot be reached within one hour.

The area that can be reached for rescue purposes of the rescue units are overlaid so that their efficiency can be seen. For instance, in Figure 9, two ships in the northeast of the rescue unit position, in the red rectangle, are isolated; the other ships in the traffic flow cannot reach them within an hour. With the area that can be reached for rescue purposes displayed, it is noticeable that the rescue ship can help the closest ship within 15 minutes and the second ship within about 30 minutes.

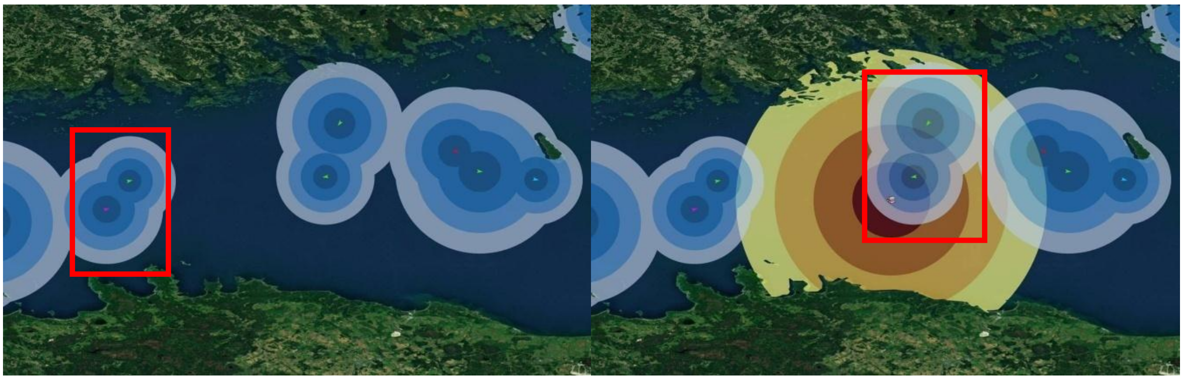

**Figure 9: The area that can be reached for rescue purposes for ships carrying an A.I.S. (left) S.A.R. area that can be reached for rescue purposes overlaid (right)**

## 5. CONCLUSIONS AND DISCUSSION

Discussions with the coastguards took place in order to obtain the opinions of potential users. The following remarks are suggestions made during the discussion.

### 5.1 Risk Analysis

#### 5.1.1 Winter Conditions

This study was performed on the basis of summer traffic; the A.I.S. data were collected while the sea was not frozen. During the winter, the traffic layout is changed and certainly the theories developed in this study cannot be applied. Ships reroute to sail behind icebreakers or closer to the shores. Therefore, it would be interesting to create a model for the wintertime as well, when the sea is frozen.

#### 5.1.2 Regular Ships

Ferries between Helsinki and Tallinn are used to sailing in the Gulf of Finland; they are aware of the hazardous areas and dangers. But in the risk model, they are weighted as if they were cruise ships coming from foreign countries, which are not always aware of the dangers. It would be better to consider regular ships with a lower probability of accidents than non-regular ships. Since the A.I.S. data carry the name, or several identification numbers, these regular ships can easily be tracked.

#### 5.1.3 Improving The Accident Probability Density Model

This study assumes that accidents that will happen are related to accidents that happened before; the closer a ship is to the site of an accident, the greater the probability of an accident. If this study is applied in an area where the history of accidents is considerable, it may be necessary to conduct a prestudy about accident relations in order to improve the accident probability model. The Accident Investigation Board (2009) publishes reports about all major accidents that occur in Finnish waters or involve a Finnish vessel, and these publications can be used to improve the accident probability model.

#### 5.1.4 Accident Knowledge Approach

The coastguards are aware of the Gulf of Finland and the hazardous areas in it. For instance, during the winter some ships sail around the “Suursaari” island to the north, while in summer the waterways are to the south. To the north of the island, there are several dangerous zones, and it would be better if the coastguards could define a polygon and give the probability of accidents over these areas, according to their own knowledge. Thus, the accident probability density model will use only either the accident history or a user-defined area or both of them.

### 5.2 Vulnerability Analysis

#### 5.2.1 Radar Targets

Several accidents are close to the shoreline and they involve small ships such as pleasure boats or sailing boats. These ships do not carry A.I.S. The only way the coastguards can detect them is with radar, because radar can return the speed of a target and it would be useful to complete the vulnerability chart using radar targets. Thus, all ships at sea could be plotted and taken into consideration in the vulnerability analysis.

#### 5.2.2 Definitions Of Settings

If this theory is applied, several settings should be editable by the user. For instance, during the night, the traffic is less heavy; it would be more useful for the user to set longer reaching times than 15, 30, 45, and 60 min. An alternative to four reaching times can also be reconsidered.

The vulnerability analysis is processed according to the current SOG; but several ships, such as ships leaving harbours, do not sail at their underway speed. The user should be able to key in several speeds manually. In this way, the coastguards will be able to predict situations at sea more easily.

#### 5.2.3 Bypass / Legal Regulations

The area that can be reached by a given ship is only computed according to the speed of this ship. In reality, obstacles at sea can affect the shape of those areas.

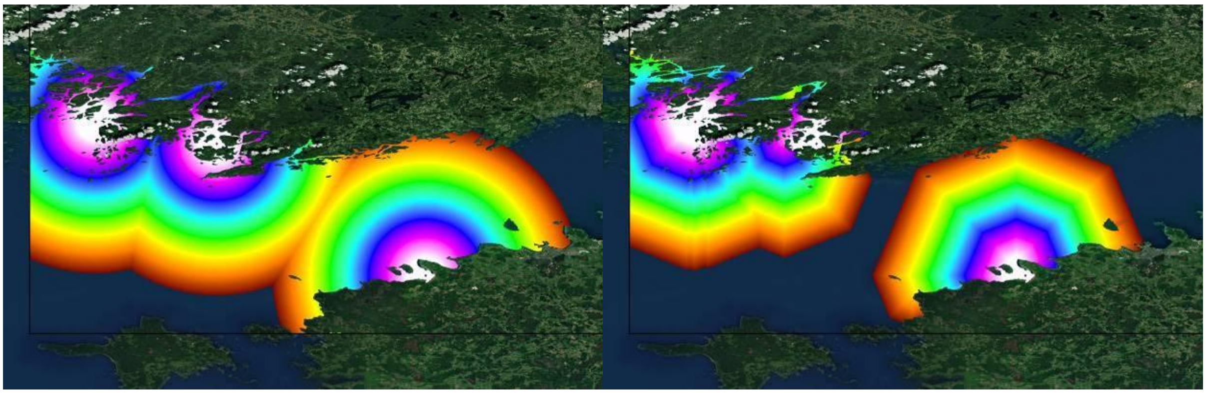
**Figure 10: Difference between straight route and bypass route (south of Turku)**

An example of accessibility with or without bypass is presented in Figure 10. The figure on the right displays polygonal shapes instead of circular shapes. This is due to the algorithm used to compute the bypass chart.

In drawing the vulnerability chart and determining isolated ships, the model is not concerned if the route taken by a ship coming to help is allowed. The closest ship may not be allowed to sail in the area where the accident takes place. For instance, a ship is not allowed to turn back in a waterway to assist a ship behind her.

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