Risk Analysis of Vessel Traffic in Delaware River

Ozhan Alper Almaz
Ph.D. Student, Department of Industrial and Systems Engineering
Rutgers, the State University of New Jersey,
100 Brett Road, Piscataway, NJ 08854-8058,
Tel: 732-445-0579 Ext. 161, Fax: 732-445-3325
e-mail: alperalmaz@gmail.com

Tayfur Altiok, Ph.D.
Professor, Department of Industrial and Systems Engineering
Program Director, Laboratory for Port Security, CAIT (Center for Advanced Infrastructure and Transportation),
Rutgers, the State University of New Jersey,
100 Brett Road Piscataway, NJ 08854-8058,
Tel: (732) 445-0579, Ext. 133, Fax: 732-445-3325
e-mail: altiok@rci.rutgers.edu

Amir Ghafoori (Corresponding Author)
Ph.D. Student, Department of Industrial and Systems Engineering
Rutgers, the State University of New Jersey,
100 Brett Road, Piscataway, NJ 08854-8058,
Tel: 732-445-0579 Ext. 166, Fax: 732-445-3325
e-mail: ghafoori@eden.rutgers.edu

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ABSTRACT

Assessment and mitigation of current risks inherent in the Delaware River and Bay (DRB) vessel traffic require the development of a post-incident recovery strategy. In this work, a model-based risk analysis in the DRB area was carried out to identify which zones of the river have higher risks, what the magnitudes are and what the possible mitigation measures may be. First a probabilistic risk model was developed considering all possible accidents as suggested by the historical data in DRB. Expert opinion elicitation process helped computing the unknown accident and consequence probabilities for various situations. Next, the risk model was incorporated into a simulation model to be able to evaluate risks and to produce a risk profile of the entire river. A scenario analysis is planned to be performed in the end in order to study the behavior of accident risks over time and geographic domain. The approach can be implemented to evaluate risks in other systems of interest as well.

Keywords: Risk analysis; Maritime traffic; Delaware River; Simulation; Expert judgment
1. INTRODUCTION

The Delaware River shoreline has a number of major petroleum refineries that process nearly 1 million barrels of crude oil per day, as well as other chemicals associated with the refining process, making it one of the most critical petroleum infrastructures in the U.S. Collectively, the Ports of Philadelphia, South Jersey and Wilmington, DE combine to be the largest general cargo port complex in the nation. Consequently, major safety vulnerabilities exist in view of the vessel traffic in the river carrying potentially combustible cargo (oil and LP gas), dry cargo (bulk and container) as well as passenger ships, among others.

The SAFE Port Act of 2006 (PL 109-711) requires Area Maritime Security Plans to include a salvage response plan intended, inter alia, to ensure that commerce is quickly restored to US ports following a transportation security incident. Accordingly, this motivates the need to study the risks inherent in Delaware River and Bay (DRB) vessel traffic, to be better able to develop a post incident recovery strategy.

Risk Analysis is one of the mostly visited and diverse areas in the literature due to its strong relevance to uncertainty and its presence in design of complex systems in a variety of application areas. The concept of risk is closely related to uncertainty. In mathematics, probability is one way to explain uncertainty although probability itself has different explanations with several perspectives. Frequency and degree of certainty are two widely accepted approaches to explain probability. In Kaplan (1), risk is explained using terms such as scenario, likelihood and consequences. A scenario represents a situation which can lead to an undesirable consequence. Likelihood is the frequency or the degree of certainty of this scenario to happen. Thus, starting with Kaplan’s arguments, risk can be expressed as the expected value of the undesirable consequence in a scenario as given in Equation (1). That is,

\[ R_s = P_s \times C_s \]  

where \( s \) represents the scenario, \( R_s \) is the risk of scenario, \( P_s \) is the probability of occurrence of the scenario and \( C_s \) is the consequence of the scenario in case it occurs.

Notice that risk has an additive property that it is a measure that can be added over various scenarios to obtain cumulative risks. Also notice that a scenario can be described as an array of variables which makes the risk a function of the same set of variables.

Thus, risk analysis can be summarized as the study of scenarios, possible consequences and relating them to their probabilities. Kaplan defines a scenario tree approach showing relation of situations and what happens next for each state. “Fault Trees” can be drawn starting from end states and going backward to the starting events giving rise to fault tree analysis. Identifying initial events and going forward to the end states is known as “Event Trees” giving rise to event tree analysis. Risk analysis can benefit from either of them in identifying its critical elements mentioned above.

In this study, the approach to evaluate risks in DRB is a hybrid one in the sense that it involves both a mathematical risk model and a simulation model developed. The details of the simulation model can be found in (2). These two models work in lock step in such a way that the simulation model generates all possible situations and passes them on to the mathematical model for risk evaluations. By repeating the risk evaluation process at every short time interval, it is possible to generate the zone-based risk profile of the entire river.

2. LITERATURE REVIEW

The risk analysis literature in the maritime domain can be categorized as applications in the safety of individual vessels and structural design using the tools of reliability engineering and probabilistic risk analysis approaches to the holistic transportation systems.

Wang (3) summarizes risk analysis tools used in maritime applications as follows:

1. Expert judgment and approximate reasoning approach for dealing with problems associated with a high level of uncertainty. This includes subjective safety-based decision-making method, evidential reasoning technique, fuzzy set modeling method and Dempster–Shafer method for risk modeling and decision making.
2. Safety-based design/operation optimization approach.
3. Application of methods developed in other disciplines, such as artificial neural network approach and Bayesian networks for risk estimation and decision making.

Soares and Teixera (4) also summarized the approaches used in risk assessment for maritime transportation. They showed, while the early applications being mostly on risks of individual vessels, more recent work have focused on decision making such as regulations to govern international maritime transportation.
In recent years, there has been an increase in the number of studies related to risk modeling and analysis in the maritime domain. Fowler and Sorgard (5) worked on ship transportation risk under the project “Safety of Shipping in Coastal Waters” (SAFECO). In their study, Marine Accident Risk Calculation System (MARC) was used which was based on causes of important accidents found in historical data. They used Vessel Traffic System (VTS) database and environment data for accident frequency calculations, fault and event tree analysis, expert judgment and physical models to calculate failure probabilities, accident frequencies and possible consequences to come up with a risk assessment. On the other hand, they defined their major uncertainty categories as traffic data and historical statistics, model for calculation of critical situations and accident probabilities. Their study could be benefited in various areas such as assessment of risk mitigation measures, determination of maritime regulations, cost-benefit analysis and risk communication among several parties affected.

Merrick et al. (6) worked on traffic density analysis which would later lead to the risk analysis for the ferry service expansion in San Francisco Bay area. They tried to estimate the frequency of vessel interactions using a simulation model they developed, in which vessel movements, visibility conditions and geographical features were included. They evaluated specific scenarios regarding ferry service expansion in the bay area and got indications for areas that high accident risks can appear.

Merrick et al. (7) developed a Bayesian simulation technique for the risk analysis in maritime applications. Utilizing this approach, it is claimed that epistemic uncertainty due to external traffic in their model as well as aleatory uncertainty due to simulation modeling itself was tried to be treated in their previous study of expansion of San Francisco Bay ferries.

In Merrick and van Dorp (8), previously developed two methodologies to perform maritime risk assessment were combined through two case studies. In the previous studies they worked on developing a Bayesian simulation to create situations for accident potential traffic (7). In another study, they developed Bayesian multivariate regression for the effect of factors on situations in the simulation and expert judgments of these situations that are creating accident risks Merrick et al., (9). Thus, they tried to perform a full scale risk assessment combining their approaches.

Ulucu et al. (10) worked on a quantitative methodology to investigate safety risks on the transit vessel traffic in the Strait of Istanbul. They analyzed the transit vessel traffic system in the Strait and developed a simulation model to mimic maritime operations and environmental conditions. The risk model employs subject-matter expert opinion in identifying probabilities regarding instigators, accidents and consequences.

Risk analysis has various interesting and widely discussed concepts and approaches in it. Due to the possible and growing application areas, it can be said that risk analysis can be a trusted decision support tool for various industries as well as for maritime industry. Besides, as the risk analysis applications increase the framework and methodologies developed can be applicable to other domains.

3. PRELIMINARIES TO RISK MODELING IN DRB

Accidents typically occur as a result of a chain of events rather than an independent single event. The initial step of the risk analysis process is to identify reasons and outcomes of accidents. This process can go into utmost detail for descriptive purposes, however when mathematical calculations are involved and data requirements are considered, the chain defining the risk framework can be limited to triggering events, accident types and consequences. FIGURE 1 shows the general risk framework.

Instigators can be defined as the major triggering events which may be followed by an accident. Thus, it is assumed that an accident cannot take place just by itself unless an instigator occurs. Based on the US Coast Guard (USCG) accident data for DRB, instigators are identified as shown below:

1. Human Error (HE) may include “not following the policies or best practice”, “communication breakdown”, “inadequate situational awareness” and etc.
2. Propulsion Failure (PF) may include “engine breakdown”, “contaminated fuel problem”, “propeller problem” and etc.
3. Steering Failure (SF) may include “hydraulic system failure”, “rudder problem” and etc.
4. Electrical / Electronic Failure (EF) may include “generator failure”, “computer software problems”, “navigation and communication system failure” and etc.
5. Other Systems Failure (OSF) may include “hull structure problems”, “cargo and cargo control systems failure” and etc.

Accidents are the unexpected and undesirable events resulting in some sort of damage. DRB accident data suggests following categorization of accidents:
Consequences typically are damages or harm to physical assets or humans as a result of an accident. Based on DRB accident data consequences are grouped into the following 3 categories:

1. Human Casualty (HC) may include death, permanent disabling injury, and minor injury
2. Environmental Damage (EnvD) may include impact to wild life and habitat, loss of commercial and recreational use, danger to human life, oil spill and etc.
3. Property Damage (ProD) may include damage to the vessel or other properties involved in the accident.

There exists a causal relationship among instigators, accidents and consequences such that instigators may lead to accidents and accidents cause consequences. Each instigator leads to specific types of accidents with a probability as given in TABLE 1. Since the relationship chain begins with an instigator, the instigator occurrence probability needs to be obtained as well. TABLE 1 also shows probability of occurrence of each instigator on a vessel based on the historical data of 1992 to 2008.

TABLE 1 Probability of Accident Occurrence Given an Instigator and Probability of Instigator Occurrence Based on 50,000 Vessels from the Historical Accident Data of 1992 to 2008

<table>
<thead>
<tr>
<th>Instigators</th>
<th>Collision</th>
<th>Allision</th>
<th>Grounding</th>
<th>Fire / Explosion</th>
<th>Sinking / Capsizing / Flooding</th>
<th>Oil Spill</th>
<th>P(Instigator)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human Error</td>
<td>0.1269</td>
<td>0.2463</td>
<td>0.3993</td>
<td>0.0560</td>
<td>0.0299</td>
<td>0.0336</td>
<td>0.0054</td>
</tr>
<tr>
<td>Propulsion Failure</td>
<td>0.0349</td>
<td>0.0349</td>
<td>0.0291</td>
<td>0.0174</td>
<td>0.0001</td>
<td>0.0058</td>
<td>0.0034</td>
</tr>
<tr>
<td>Steering Failure</td>
<td>0.0566</td>
<td>0.0377</td>
<td>0.0943</td>
<td>0.0002</td>
<td>0.0002</td>
<td>0.0755</td>
<td>0.0011</td>
</tr>
<tr>
<td>Electrical / Electronic Failure</td>
<td>0.0003</td>
<td>0.0256</td>
<td>0.0513</td>
<td>0.0513</td>
<td>0.0003</td>
<td>0.0003</td>
<td>0.0008</td>
</tr>
<tr>
<td>Other Systems Failure</td>
<td>0.0074</td>
<td>0.0662</td>
<td>0.0662</td>
<td>0.0735</td>
<td>0.1029</td>
<td>0.2941</td>
<td>0.0027</td>
</tr>
</tbody>
</table>

Numbers in TABLE 2 shows the probability of every type of consequences as a result of accidents. The values in TABLE 1 and TABLE 2 are calculated based on the 17 years of accident data provided by USCG headquarters in Washington D.C. These numbers are used later in the calibration process.
TABLE 2 Probability of Consequence Occurrence Given an Accident and Based on the Historical Accident Data of 1992 to 2008

<table>
<thead>
<tr>
<th>Accidents</th>
<th>Consequences</th>
<th>Human Casualty</th>
<th>Environmental Damage</th>
<th>Property Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision</td>
<td></td>
<td>0.0417</td>
<td>0.0833</td>
<td>0.8750</td>
</tr>
<tr>
<td>Allision</td>
<td></td>
<td>0.0435</td>
<td>0.0761</td>
<td>0.8804</td>
</tr>
<tr>
<td>Grounding</td>
<td></td>
<td>0.0368</td>
<td>0.0588</td>
<td>0.9044</td>
</tr>
<tr>
<td>Fire / Explosion</td>
<td></td>
<td>0.2273</td>
<td>0.0682</td>
<td>0.7045</td>
</tr>
<tr>
<td>Sinking / Capsizing / Flooding</td>
<td>0.0294</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil Spill</td>
<td></td>
<td>0.0800</td>
<td>0.7200</td>
<td>0.2000</td>
</tr>
</tbody>
</table>

Beside the described causal relationship, there are other factors that may increase or decrease the chances of an instigator or accident happening or the scale of consequences. They are referred to as situational attributes. For example, the probability of collision may increase due to loss of visibility or due to bad weather conditions. Generally these attributes are classified into two groups; vessel attributes and environmental attributes.

Each situational attribute has its finite number of states. These states are given in TABLE 3 below. Among these attributes $X_3$ and $X_4$ are vessel attributes and the rest are environmental. Note that there are a total of 25,920 different possible situations for the selected set of 8 situational attributes and the possible number of states for each attribute. This immediately justifies the need to develop a model to keep track of the dynamics of the causal chain introduced above and the evaluation of the resulting risks.

TABLE 3 Situational Attributes Influencing Instigators, Accident Occurrence and the Consequences

<table>
<thead>
<tr>
<th>Variable</th>
<th>Situational Attribute</th>
<th>Possible Values</th>
<th>States</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_1$</td>
<td>Time of Day</td>
<td>2</td>
<td>Day, Night</td>
</tr>
<tr>
<td>$X_2$</td>
<td>Tide</td>
<td>2</td>
<td>High, Low</td>
</tr>
<tr>
<td>$X_3$</td>
<td>Vessel Status</td>
<td>3</td>
<td>Docked, Underway, Anchored</td>
</tr>
<tr>
<td>$X_4$</td>
<td>Vessel Class</td>
<td>10</td>
<td>General Cargo &lt; 150m, General Cargo ≥ 150m, Tugboat / Barge, Passenger ≥ 100GT, Petroleum Tanker &lt; 200m, Petroleum Tanker ≥ 200m, Chemical Tanker &lt; 150m, Chemical Tanker ≥ 150m, LNG / LPG, Lightering Barge</td>
</tr>
<tr>
<td>$X_5$</td>
<td>Zone</td>
<td>6</td>
<td>Delaware Bay, CD Canal Region, Wilmington Region, Paulsboro Region, Philadelphia Region, Upper Delaware River</td>
</tr>
<tr>
<td>$X_6$</td>
<td>No. of Vessels within 5NM</td>
<td>3</td>
<td>0 or 1 vessel, 2 to 3 vessels, more than 3 vessels</td>
</tr>
<tr>
<td>$X_7$</td>
<td>No. of Vessels Anchored in the Zone</td>
<td>3</td>
<td>0 or 1 vessel, 2 to 3 vessels, more than 3 vessels</td>
</tr>
<tr>
<td>$X_8$</td>
<td>Season</td>
<td>4</td>
<td>Fall, Winter, Spring, Summer</td>
</tr>
</tbody>
</table>
Almaz, O.A., Altiok, T. and Ghafoori, A.

Based on geography and the existing terminals, we have divided DRB into 6 zones for risk analysis purposes as shown in FIGURE 2. These zones are used in a simulation model to obtain zone risks.

FIGURE 2 Delaware River and Bay divided into 6 zones.
Almaz, O.A., Altiok, T. and Ghafoori, A.

4. MATHEMATICAL RISK MODEL

The underlying mathematical risk formulation for a set of vessels in a given zone is given below. In this formulation \( R_s(X) \) represents the instantaneous risk for a given zone \( s \) based on the states of the situational attributes as observed at a given instance.

\[
R_s(X) = \sum_{v \in S_v} \sum_{j \in I} \left( \sum_{k \in C} E\left[ C_{k,j,v} | A_{j,v}^t, X_v^t \right] \times \Pr\left( A_{j,v}^t | X_v^t \right) \right)
\]

(2)

where

\[
\Pr\left( A_{j,v}^t | X_v^t \right) = \sum_{i \in I} \Pr\left( A_{j,v}^t | I_{i,v}^t, X_{i,v}^t \right) \times \Pr\left( I_{i,v}^t | X_{i,v}^t \right)
\]

(3)

and

- \( s \) : zone no
- \( v \) : vessel no
- \( i \) : instigator type
- \( j \) : accident type
- \( k \) : consequence type

- \( X_{i,v}^t \) : Situational attribute set for instigator \( i \), regarding vessel \( v \) in zone \( s \)
- \( I_{i,v}^t \) : Instigator type \( i \), regarding vessel \( v \) in zone \( s \)
- \( A_{j,v}^t \) : Accident type \( j \) regarding vessel \( v \) in zone \( s \)
- \( C_{k,j,v} \) : Consequence type \( k \) due to accident type \( j \) regarding vessel \( v \) in zone \( s \)
- \( J_j \) : \( \{1,..,5\} \) is the set of instigators for accident type \( j \)
- \( C_j \) : \( \{1,..,3\} \) is the set of consequences for accident type \( j \)
- \( A \) : \( \{1,..,6\} \) is the set of accidents
- \( S_v \) : is the set of vessels navigating in zone \( s \) at the observed instance.

Finally, \( E\left[ C_{k,j,v} | A_{j,v}^t, X_v^t \right] \) is the expected consequence given the accident and the set of situational attributes and \( \Pr\left( A_{j,v}^t | X_v^t \right) \) is the probability of accident occurrence given the set of situational attributes.

Based on the above risk formulation, there are number of questions to be answered in order to quantify risks as shown below:

1. How frequent does any particular situation occur?
2. For a given situation, how often do instigators occur?
3. If an instigator occurs, how likely is a particular accident?
4. If an accident occurs, what would be the expected damage to human life, environment and property?

In this study, risks are quantified based on historical accident data, expert judgment elicitation and the simulation model of vessel traffic in the Delaware River and Bay introduced earlier. The main use of the simulation model is to generate all the possible situations in a realistic manner (recall 25,920 situations mentioned earlier) and to make the underlying mathematical calculations. Historical accident data provides the probabilities for instigators, accidents and consequences. At last, expert judgment elicitation provides the link between all possible situations and their probabilities.

As introduced in FIGURE 2, Delaware River is divided into 6 zones in the simulation model. The risk in each zone is calculated based on a snapshot taken at every properly chosen \( \Delta t \) time units. In a snapshot, situational attributes for each vessel in a specified zone is available. Thus, risk contribution of each vessel in a particular zone is calculated and aggregated into the zone risk \( R_s(X) \). Although instantaneous risks are not continuously tracked, taking snapshots based on a time interval provides sufficiently random and numerous data points. Therefore, the expected risk for a specific zone is obtained by averaging \( R_s(X) \) over the number of snapshots taken.

Although historical data provides expected probability of an instigator occurrence per vessel, expected accident probability given an instigator and expected probability of a consequence given an accident these probabilities clearly affected by different situations. That is, the probability of an instigator to occur during day time compared to night time
might be different. Each situation and their levels have different effects on these probabilities. Due to lack of data, given a situation estimation of any probability in this context requires expert judgment elicitation.

In this study, expert judgment elicitation is performed through direct questioning to evaluate the effects of situations and levels of situations on each instigator, accident given an instigator and consequence given an accident. The participants in elicitation were the members of the Area Maritime Security Committee including the USCG and the port stakeholders. The participants had years of experience in navigation in waterways.

For a given event \( \Phi \), the effect of a situation (time of day, tide, vessel class, ... etc.) is represented by \( \beta \) and the effect of a level of a situation (day / night, high tide / low tide, tanker / general cargo, ... etc.) is represented by \( X \) which is also called cardinality of a level of a situation. In this formulation, \( P_\phi \) is the calibration constant which calibrates the associated probability using historical data.

\[
\Pr(\Phi|X) = P_\phi(\beta^T X) = P_\phi(\beta_1 X_1 + ... + \beta_n X_n)
\]  

(4)

4.1. Probability of an Instigator Given a Situation

Based on the discussion above, the probability of an instigator given a particular situation can be estimated using the following formulation.

\[
\Pr(I_i|X_i) = P_i(\beta_i^T X_i)
\]  

(5)

Through expert judgment elicitation process, \( \beta \) and \( X \) values are obtained and directly used in the risk formulations. Sample questionnaires used in expert elicitation to collect \( \beta \) and \( X \) values are given in FIGURE 3.

In \( \beta \) questionnaires for instigators, the effect of a situational attribute on the occurrence of an instigator in a particular vessel is asked to the experts. Experts are expected to put a value between 0 (no relation) and 100 (direct relationship / correlation) to the blocks provided. For some questions blocks are grayed out since the combination being measured by that block would be unlikely or impossible to occur. However, answers are still permitted if the experts think that there might be a relation. While evaluating risks, situational attribute values shown in FIGURE 3 were averaged over individual responses and later scaled down to less than 1.0.

In \( X \) (cardinality) questionnaires, the importance of a level of a situational attribute on the occurrence of an instigator in a particular vessel is asked to the experts. Experts are again expected to put a value between 0 (no relation) and 100 (direct relationship / correlation) to the blocks provided where grayed out blocks are still optional. In order to simplify the questionnaires, vessel type question is separately asked for any type of instigator. However, these answers are weighted using vessel class values and replaced to be used in the formulation.

4.2. Probability of an Accident Given an Instigator and a Situation

The probability of an accident given an instigator is taking place in a particular situation can be estimated using the formulation given below.

\[
\Pr(A_j|I_i, X_i) = P_{ij}(\beta_{jj}^T X_{jj})
\]  

(6)

Through the expert judgment elicitation process, again \( \beta \) and \( X \) values are obtained and directly used in the formulations. Sample questionnaires to collect \( \beta \) and \( X \) values are prepared in a similar way as given in FIGURE 3. \( \beta \) questionnaires for accidents are prepared for all accident types separately. In questions, given an instigator taking place on a particular vessel, the effect of a situational attribute on the likelihood of an accident is asked to the experts.

\( X \) (cardinality) questions for accidents are combined into one questionnaire for any type of accident. The main reason for this simplification is due to the assumption that the levels of situational attributes have very similar effects on all accident types in consideration. In questions, given an instigator taking place on a particular vessel, the importance of attribute levels on the likelihood of an accident is asked to the participants.

4.3. Expected Consequence Given an Accident and Situation

Expected consequence given an accident has happened in a particular situation can be estimated using the formulation given below.

\[
E\left[C_{k,j} \bigg| A_j, X_k\right] = C_{k,j} \cdot \Pr\left(C_{k,j} \bigg| A_j, X_k\right)
\]  

(7)

where \( C_{k,j} \) represents the impact level due to consequence type \( k \) and accident type \( j \) and the probability of a consequence given an accident has happened in a particular situation can be estimated using the formulation given below.

\[
\Pr\left(C_{k,j} \bigg| A_j, X_k\right) = P_{kj} \cdot (\beta_{kj}^T X_k)
\]  

(8)
Through expert judgment elicitation process, again $\beta$ and $X$ values are obtained and directly used in the formulation. Sample questionnaires to collect $\beta$ and $X$ values are prepared in a similar manner to other questionnaires as given in FIGURE 3.

<table>
<thead>
<tr>
<th>Situational Attributes</th>
<th>HE</th>
<th>PF</th>
<th>SF</th>
<th>EF</th>
<th>OSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Time of Day</td>
<td>80</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>2. Tide</td>
<td>80</td>
<td>25</td>
<td>25</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>3. (Your) Vessel Status (e.g. Docked, Underway, Anchored)</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>4. (Your) Vessel Class (e.g. General Cargo, Dangerous Cargo)</td>
<td>50</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>5. Zone (e.g. 1,2,3,4,5,6)</td>
<td>80</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>6. No. of Vessels Underway within 5 NM of your position</td>
<td>85</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>7. No. of Vessels Anchored within your Zone</td>
<td>60</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>8. Season</td>
<td>75</td>
<td>30</td>
<td>30</td>
<td>10</td>
<td>50</td>
</tr>
</tbody>
</table>

A sample of $\beta$ questionnaire

<table>
<thead>
<tr>
<th>Instigator</th>
<th>HE</th>
<th>PSF</th>
<th>OSF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Time of Day</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Day</td>
<td>30</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>b. Night</td>
<td>80</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>2. Tide</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. High</td>
<td>50</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>b. Low</td>
<td>80</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>3. (Your) Vessel Status</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Docked</td>
<td>0</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>b. Underway</td>
<td>90</td>
<td>90</td>
<td>50</td>
</tr>
<tr>
<td>c. Anchored</td>
<td>30</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>4. (Your) Vessel Class</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. General Cargo</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>b. Dangerous Cargo</td>
<td>60</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>5. Zone (Geographical – Infrastructure only)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. 1</td>
<td>50</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>b. 2</td>
<td>60</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>c. 3</td>
<td>60</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>d. 4</td>
<td>70</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>e. 5</td>
<td>70</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>f. 6</td>
<td>60</td>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>6. No. of Vessels Underway within 5 NM of your position</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. 0-1</td>
<td>60</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>b. 2-3</td>
<td>70</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>c. more than 3</td>
<td>75</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>7. No. of Vessels Anchored within your Zone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. 0-1</td>
<td>20</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>b. 2-3</td>
<td>30</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>c. more than 3</td>
<td>50</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>8. Season</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Fall</td>
<td>60</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>b. Winter</td>
<td>80</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>c. Spring</td>
<td>70</td>
<td>60</td>
<td>10</td>
</tr>
<tr>
<td>d. Summer</td>
<td>50</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>

A sample of $X$ questionnaire

FIGURE 3 Sample questionnaire for assessing the effects of situational attributes on instigator occurrence.
\( \beta \) questionnaires for consequences are prepared based on all accident types separately. In questions, given an accident has happened, the effect of a situational attribute on the severity of the consequence is asked to the experts.

\( X \) (cardinality) questions for consequences are combined into one questionnaire based on any type of accident. The main reason for this simplification is due to the assumption that the levels of situational attributes have very similar effects on all consequences in consideration. In questions, given an accident has happened, the importance of attribute characteristics on the severity of the consequence is asked to the participants.

4.4. Consequence Impact Levels

Evaluation of consequences is a major challenge in risk analysis. The impact level is represented as \( C_{kj} \) in Equation (7) for consequence type \( k \) and accident type \( j \). Below we summarize our efforts to quantify accident consequences in the DRB area.

Quantification of Human Casualty

When there is human casualty after an accident, number of injuries and/or deaths are estimated from the empirical distribution based on historical data. We suggest using the U.S National Safety Council comprehensive cost values from 2009 (11) to estimate total human casualty costs.

Quantification of Environmental Damage

Environmental damage costs are estimated based on oil spill historical data per given vessel types. It is independent of the accident type since historical data does not suggest significant difference for different accidents. For a given incident, total oil spill amount is estimated from the empirical distributions per vessel type and total comprehensive costs are calculated. Comprehensive oil spill costs per gallon covering response costs, environmental damage costs, and the socioeconomic costs are used based on Etkin (12). Note that comprehensive costs values are adjusted to 2011 values with inflation rates.

Quantification of Property Damage

Property damage costs are estimated based on historical data for a given accident type. For each accident type, empirical distributions are fit to estimate total property damage costs. Note that costs from the historical data are adjusted to 2011 values by applying inflation rates.

4.5. Calibration of Probabilities

Validation process of the accident probabilities in risk calculations involves a calibration process. It is about comparing probabilities from the model with the ones from the historical data, to the extent of their availability. This is achieved by making an initial simulation run with the calibration constants in the risk model being 1.0. After running the model long enough, each probability (such as probability of collision given human error) is averaged over time and over all situations in the model. This measure is a proper value to be compared with the same probability calculated from the historical data. Hence to calculate the calibration constant, every probability from the historical data is divided by its corresponding counterpart from the model. The ratio is the calibration constant and replaces the ones in the preliminary run of the model, making the model ready for risk calculations. In essence, this operation can be described by the following:

\[
\Pr\left(C_{k,j} \mid A_j, X_k\right) = P_{k,j}(\beta^{T}_{k,j} X_k) \quad \Rightarrow \quad P_{k,j} = \frac{\Pr\left(C_{k,j} \mid A_j, X_k\right)}{\beta^{T}_{k,j} X_k}
\]

4.6. Risk Evaluations

The aforementioned risk model (Equation 2) is integrated into the simulation which is capable of producing all possible situations regarding both the vessel traffic and the situations in the river. The mathematical risk model and the simulation model work hand in hand in such a way that the risk model responds with the corresponding risk evaluation for every possible situation generated in the simulation model. This process is carried out at every short time interval (i.e., 60 minutes) at each zone to produce a temporal risk profile of the entire river. At every time step, using the situation attribute values, the risk model calculates probabilities of all types of accidents to occur given the situation at the time. Then the model uses these probabilities to calculate corresponding risks. Clearly, this is a process that is computationally intensive especially if the risk profiles are required to be precise indicating frequent evaluations. Results of risk calculation in the model are saved in an output file for further analysis and demonstration purposes.
5. NUMERICAL RESULTS

Based on the risk model introduced earlier, the simulation model is run for 30 years with 10 replications and the results of the risk model are presented and analyzed in this part to provide an insight of the risk profile for the current situation of the river based on past data. All risk estimates are expressed in financial terms that are in dollars.

FIGURE 4 illustrates a 3D risk profile of the DRB throughout a 24 time horizon. In this figure the risk values of a full year are mapped into a 24 hour time frame, such that the “Time of Day” axis shows the real time of day when the corresponding risk value has been observed by the model. Looking at this figure from the “Zone” axis clearly induces that high risk values happen in 1st, 3rd and 4th zones more frequently comparing with the other three zones.

FIGURE 4 3D risk profile of Delaware River based on zones and time of day.

In FIGURE 5 the height of each bar shows the average total risk (in dollars) for a given zone in DRB. Again the average risks for zones 1, 3 and 4 are higher than the risks for other zones. Different colors in each bar show the relative importance of the corresponding consequence type in the total risk figure for that zone. Almost in all zones environmental damage (EnvD) is the dominant consequence of all. This is plausible for zones 1, 3 and 4. In zone 1 the risk of environmental damage is high due to a great deal of lightering activity in Big Stone Beach Anchorage. Frequency of visits and length of stay for tankers in zones 3 and 4 are higher than the ones in other zones as a result of higher number of oil terminals. Therefore the probability of occurrence of environmental damage is higher and consequently the expected environmental damage and expected risks are higher in these zones.
FIGURE 5 Zone risks classified by the consequence type.

FIGURE 6 shows the same risk values as FIGURE 5, but the risks are classified based on accident types in each zone. This is to better understand the contribution of each accident to zone risks. As suggested by the figure, Oil Spill (OS) and Grounding (G) seem to be the major accidents having the biggest contributions to risks in DRB. This is apparently reasonable considering the extensive tanker activity and the depth limitations in the river.

FIGURE 6 Zone risks classified by accident types
6. CONCLUSION

Delaware River has a number of major petroleum refineries processing crude oil and other chemicals making it one of the most critical petroleum infrastructures in the U.S. This motivates the need to study the risks inherent in Delaware River and Bay vessel traffic, in order to prepare better plans for a post incident recovery strategy.

In view of this, we have developed a model-based approach for risk analysis to study potential incidents that would result in dire consequences due to stoppage of maritime traffic in the river. The approach considers the causal chain of events with all possible instigators, accidents and consequences, and uses the classical approach of Probability x Consequence to evaluate risks over all situations, time and geography. The model was instrumental in estimating key parameters essential to risk computations. A particular risk measure that is the sum of the expected consequences of various potential incidents was used in the analysis to quantify the risks in DRB. The approach is such that the mathematical risk model associates a risk value with every possible situation generated by the simulation model. Repeating this procedure over time and geography, a risk profile was obtained to show dynamic maritime risks in each of the 6 zones over a year. The risk profile shows where the higher levels of safety risks are in the river and suggests mitigation ideas.

The model has suggested that the risks in zones 1, 3 and 4 are much higher compared to the rest of the river. This is mainly due to tanker and crude handling operations including lightering in Big Stone Beach Anchorage and loading and unloading operations in terminals upstream.

7. ACKNOWLEDGEMENTS

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8. REFERENCES