SYSTEM SIMULATION: A RISK MANAGEMENT TOOL FOR PRINCE WILLIAM SOUND[1]

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ABSTRACT: *The Prince William Sound (PWS) risk assessment was a joint project of Det Norske Veritas (DNV), Rensselaer Polytechnic Institute (RPI), and the George Washington University (GWU). The technique of system simulation developed by GWU was one of three risk analysis methodologies used in the PWS risk assessment. The system simulation methodology is based on the premises that risk is a dynamic property of a system, and that the judgment of experts who have a deep understanding of the system can be used to compensate for incomplete data. The system simulation was used to assess the baseline or current risk in the PWS oil transportation system and to evaluate the effectiveness of potential risk reduction measures. The PWS risk assessment found that current system safeguards effectively address significant system risks, but are not optimal. The dynamic interactions modeled in the simulation demonstrate that actions that reduce risk in one part of the system often increase risk in other parts. The ability to identify and to evaluate these risk tradeoffs is an essential element of risk management. The PWS risk assessment identified specific interventions that could increase the level of safety of oil transportation in Prince William Sound.*

This paper provides an overview of the methodology and results of the recently completed Prince William Sound (PWS) risk assessment project and describes in detail the project's innovative application of system simulation to the problems of risk assessment, risk reduction, and risk management. The use of dynamic simulation, a unique facet of the PWS risk assessment, made it possible to measure the systemwide impact of dynamic interventions such as closure restrictions and escort requirements. The PWS risk assessment project was a joint project of Det Norske Veritas (DNV), Rensselaer Polytechnic Institute (RPI), and the George Washington University (GWU). The project was directed by a steering committee composed of the Prince William Sound Shipping Companies (ARCO, Sea River, British Petroleum, Chevron, and Tesoro), the Prince William Sound Regional Citizens Advisory Committee (RCAC), the Alaska Department of Environmental Conservation (ADEC), and the U.S. Coast Guard (USCG).

The PWS risk assessment project had three primary objectives: (1) to identify and evaluate the risks of oil transportation in PWS, (2) to identify, evaluate, and rank proposed risk reduction measures, and (3) to develop a risk management plan and risk management tools that can be used to support a risk management program. The involvement of all TAPS shippers, the Regional Citizen's Advisory Council, Alyeska, the Coast Guard, and the State of Alaska DEC in the management of the project provided the study team with unique access to individuals and information and ensured that all viewpoints are considered in the analysis.

The risk of an accident is defined as the product of the probability of occurrence of the accident and the consequences of that accident. An accident is an event such as a collision or grounding that has adverse consequences (e.g., injury, loss of life, economic loss, environmental damage). An incident is an error such as a wrong course change or a failure such as a loss of propulsion that creates an unsafe condition that may result in an accident. The USCG uses the term *vessel casualty* to describe both incidents and accidents. The PWS risk assessment differentiates between triggering events (incidents) and events with direct adverse consequences (accidents).

The PWS risk assessment did not attempt to determine an "acceptable level of risk" a priori. Rather, the analysis described and measured the current level of risk in the system and identified and measured the potential effectiveness of risk reduction measures. The determination of acceptable risk will be a product of the stakeholder's use of the PWS analysis; it was not an initial parameter subjectively determined or a value calculated from some other environment.

The study scope addressed the risks of marine oil transportation from the Valdez Marine Terminal to 20 miles outside of Hinchinbrook Entrance. It examined causal and contributory factors such as marine traffic, weather, external environmental variables, human error, and mechanical failure. The study included technical and operational aspects of the tanker fleet, regulatory requirements, and operating company management. Excluded from the scope of the study were events that could occur within the terminal itself or events caused by certain extremely-low-probability natural phenomena (e.g., a lightning strike, earthquake). The project approach integrated a system-oriented simulation-based methodology with more traditional statistical and event-oriented probabilistic methods. Historical data analysis and structured expert judgment were used to support each element of the modeling process.

Project methodology

The methodology developed for the Prince William Sound risk assessment consisted of four interrelated stages:

1. The input stage consisted of gathering data and information and constructing databases.

1. Opinions or assertions expressed in this paper are solely those of the authors and do not necessarily represent the views of individuals or organizations composing the PWS Risk Assessment Steering Committee or other members of the PWS risk assessment contract team.

2. The synthesis stage consisted of analyzing these data and information and producing the input required by the assessment methodologies.
3. The assessment stage required the building, testing, and application of Prince William Sound specific risk assessment models.
4. The evaluation stage consisted of providing a risk profile of the current system (baseline risk) and the evaluation of proposed risk reduction measures.

Since no single risk assessment methodology could provide the level of detail required by this analysis, four methodologies were linked to provide the assessment capability. Three methodologies were used to assess the frequency of incidents and accidents. A single oil outflow model was used to calculate a surrogate measure of the expected impacts of accidents predicted by the other three methodologies. The methodology of fault trees and event trees was used to examine specific high-interest hazard scenarios that could not be examined in detail by other methodologies, such as powered grounding in the Narrows, allision at the dock, and collision with ice. Fault trees provide insight into the causal chains producing these significant events and can be used to determine where and how risk reduction measures interrupt these causal chains. The DNV Marine Accident Risk Calculation System (MARCS) provided a static statistical picture of the risk for all accident types at all locations. The statistical model provided a systemwide perspective on what events are likely to happen and where they are likely to occur. The statistical model is uniquely suited for evaluating measures that change system parameters (e.g., evaluation of the save potential of escort tugs of different capabilities). A system simulation developed by GWU, described in detail below, provides a dynamic picture of risk. The simulation methodology is needed to evaluate risk reduction measures that affect the dynamics of the system (traffic control) or the relative risk of system states (improved human performance, vessel reliability).

The data used in the analysis included failure data for the PWS tanker calling fleet, worldwide accident data (used in fault trees and MARCS model), PWS accident and incident data (used to modify worldwide accident data), and PWS specific weather, ice, visibility, and traffic data. A management system assessment of the PWS oil shipping companies and vessels, performed by DNV auditors, was used as the basis for determining relative differences in organizational parameters used in the assessment methodologies.

The system simulation

The dynamic simulation approach to maritime risk was developed to compensate for two real-world constraints on the current state of the art of risk assessment:

- A comprehensive causal analysis of a busy port or waterway would require the creation of a complete logical construct representing all possible causal chains in the system. Existing research and data do not provide a basis for this complex construct.
- Data describing human error and other basic failures are not available. The data that are available are partial, misleading, or not applicable to the PWS system.

The system simulation methodology is based on two assumptions: (1) risk is a dynamic property of the maritime system, and (2) the judgment of the experts that have a deep understanding of the system provide a more accurate basis for the calculation of risk than do the sparse data. In this view, illustrated in Figure 1, the attributes of a vessel and the characteristics of the vessel's owner and operator are predictors of the likelihood that the vessel will experience a mechanical failure or human error. The situational attributes of the waterway (waterway configuration, location, traffic density, weather, current, etc.) will determine if that incident will become an accident. In the language of probability, the system simulation is based on conditional probabilities: the probability that an incident will occur is conditioned upon the vessel; the probability that an accident will occur is conditioned upon both the situation and the occurrence of a triggering incident. The dynamic risk assessment process, therefore, required four distinct steps:

- the calculation of the relative probability that a vessel reliability failure or human or organizational error would occur on each vessel in the Alaskan fleet,
- the calculation of the relative probability that an error or a failure occurring on a tanker would result in an accident under different situational conditions,
- the calculation of the frequency of occurrence of each situational condition, and
- the calculation of the frequency of occurrence of each accident type, including calibration against actual incident and accident data.

The attributes used to describe tankers and situations in the PWS system simulation are shown in Table 1.

Four categories of vessel reliability failures were defined on the basis of the most common technological (nonhuman) causes of maritime accidents, as shown in Table 2. Table 3 describes five types of basic human and organizational errors that were defined on the basis of the USCG *Prevention Through People* report (1995). The premise of the dynamic simulation is that the probability of these failures is conditional on the vessel and the owner and operator organization.

The relative probability that, given a vessel type, a vessel reliability failure or a human and organizational error would occur was calculated on the basis of data elicited from over 100 PWS maritime experts intimately familiar with the Alaskan tanker fleet. The questionnaires used to elicit these expert judgments were based on the technique of paired comparisons; the experts were asked to compare hundreds of pairs of vessel and organizational descriptions. The experts that completed detailed questionnaires included PWS tanker masters, chief mates, and chief engineers, and South West Alaska Pilot Association (SWAPA) pilots.

The triggering events (or incidents) in the risk model were the vessel reliability failures (VRFs) described in Table 2 and the vessel operational errors (VOEs) that result from the human and organizational errors described in Table 3. Four categories of triggering vessel operational errors were defined, as shown in Table 4.

The relative probability that, given the occurrence of a VRF or VOE in a particular situation, an accident would occur was also calculated using data obtained through expert elicitation. In this round of elicitation, questionnaires were given to local maritime experts such as fishermen and other licensed mariners engaged in operations within PWS in addition to the tanker officers and pilots.

The role of the simulation is to count how many times each opportunity for a vessel reliability incident or a vessel operational error will occur in a well-defined time period. In the PWS risk assessment, 1995 was selected as the base case year, and 25-year runs using the base case input data were used to produce a base case risk picture. In order to do this, the simulation had to present an accurate picture of the dynamics of the system: it had to accurately portray the dynamic changes in weather conditions, ice conditions, traffic, and traffic conditions. In PWS, the waterways management rules (VTS rules, industry closure conditions) and escort rules had to be accurately represented. The simulation also had to capture the complexity of the PWS fisheries, tour boat, and cruise line operations.

The relative incident and accident probabilities computed in the simulation were converted to absolute probabilities using actual data. The data used were failure rate data reported by companies whose internal reporting systems were evaluated as outstanding by DNV, actual incident data for PWS collected and processed by RPI, the projected collision rate for specific areas calculated by the DNV MARCS model, and selected accident data. Figure 2 shows how the simulation combines all available data with expert judgment to produce a systemwide risk picture. Figure 3 is a screen print of the simulation in operation. The chart on the left was produced from the scanned image of the VTS operating area. The right-hand side of the figure shows how the simulation keeps track of opportunities for incident and relative incident probabilities as it runs.

Description of project results

The project developed a range of products that provided a basis for recommendations for the effective measurement, monitoring, and man-

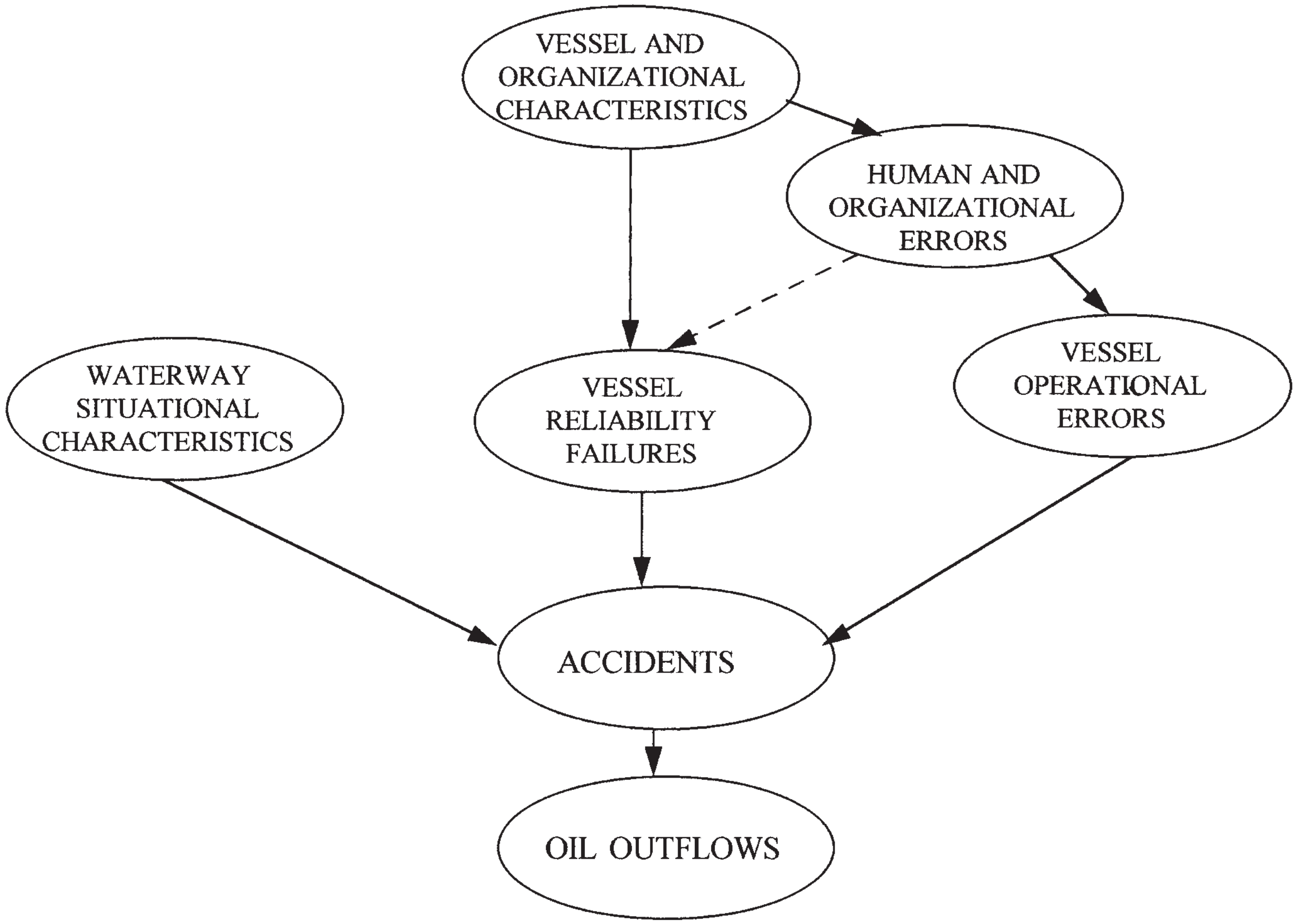

Figure 1. Influence diagram illustrating conditional relationships used in PWS system simulation

agement of risk in Prince William Sound. These products were delivered in four sets: (1) a detailed description of the current system and of current system hazards, (2) an evaluation of the current or baseline system risk, (3) a description of risk reduction measures, and (4) an evaluation of risk reduction interventions (Note: The final specific quantitative results of the risk assessment will be released by the PWS Risk Assessment Steering Committee; this paper will provide general conclusions and observations drawn from the analysis.)

The description of the baseline risk of the PWS system was described in terms of three parameters: (1) *frequency,* expressed in the expected number of accidents per year, (2) *impact,* expressed in the expected oil outflow in barrels per year, and (3) *frequency-impact relationship,* described by a distribution showing the expected frequency for discrete size ranges of expected oil outflows. The risk assessment identified and measured the impacts of risk reduction measures currently implemented in PWS, such as the escort vessel program, vessel traffic management, and closure restrictions at the Narrows and at Hinchinbrook Entrance. The assessment identified several areas where the current system has not

Table 1. Waterway and vessel attributes

Vessel attribute	Waterway attribute
Vessel size	Location
Vessel age	Traffic proximity
Vessel material (high tensile or mild steel)	Traffic type
Vessel hull type (single, dbl bottom, dbl hull)	Traffic direction
Officer type (U.S., Int'l, union, company)	Escort vessels
Officer years service on vessel	Wind speed
Officer years service in billet	Wind direction
% of officers sailing below license	Visibility
Bridge team stability	Ice conditions
Officer training (individual, team)	Current
Management type (oil co. owned, charter)	Own vessel type
Flag (U.S., other)	

Table 2. Vessel reliability failures

Failure classification	Description
1 Vessel propulsion failure	A loss of the vessel's ability to propel itself through the water (e.g., loss of boiler, turbine, main diesel, loss of propeller, broken shaft)
2 Vessel steering failure	Loss of the vessel's ability to control its rudder (e.g., steering gear or steering motor failure, jammed or lost rudder)
3 Vessel electrical power failure	Loss of the ship's electrical power to all critical systems such as navigation and lighting
4 Vessel structural failure	Cracking of the vessel's hull while under way

Table 3. Organizational and human errors

Human/organizational error classification	Description
1 Diminished ability	Physical, mental, motivational, or emotional conditions that degrade performance
2 Hazardous shipboard environment	Poor ergonomic design, poor maintenance, or poor vessel housekeeping
3 Lack of knowledge, skills, or experience	Lack of general professional knowledge, ship-specific knowledge, knowledge of role responsibility, or language skills
4 Poor management practices	Poor supervision, faulty management of resources, inadequate policies and procedures
5 Faulty perceptions or understanding	Inability to correctly perceive or understand external environment

optimally reduced risk. Four major remaining areas of significant risk in the system were identified:

- The risk of powered grounding in the Narrows, although significantly reduced by the current escort procedures and closure restrictions, is not optimal because of tanker-tethered tug procedures that do not adequately account for potential error or failure on the tug.
- The risk of drift grounding in Hinchinbrook Entrance optimally is reduced by current escort procedures because of the inability of current escort tugs to save a disabled tanker under all conditions.
- The risk of collision throughout the system has not been decreased by current system safeguards.
- Current safeguards do not reduce the risk of collision or grounding for inbound tankers in ballast.

Risk reduction

The motivation for the PWS risk assessment was to develop a risk management plan that would create a process of continued risk reduction. A logical and valid method for identifying, analyzing, and evaluating risk reduction measures was therefore an essential component of the PWS risk assessment. The eight-step process described below was developed to meet this need:

Table 4. Vessel operational error classification

Vessel operational error classification	Description
1 Poor decision making	Navigation or ship-handling error due to failure to obtain, use, or understand critical information
2 Poor judgment	Ignoring potential risks, using excess speed, passing too close, etc.
3 Lack of knowledge	Inaccurate knowledge of position and situation, inability to use navigational equipment and aids
4 Poor communications	Confusing or misunderstood communication within bridge team, or between vessel and VTS

Step 1 *Collect risk reduction measures:* Risk reduction measures were identified from three primary sources: the public record, prior studies and reports, and the steering committee.

Step 2 *Group risk reduction measures by function:* The 162 risk reduction measures identified in step 1 were organized by creating a three-level functional decomposition that categorized the measures based on functional implementation objectives in order to provide an understandable and logical presentation of the risk reduction measures. The upper level of the classification consisted of the following five functional objectives:

1. Externally control and support vessel movement
2. Improve human performance of shipboard personnel
3. Improve ships by design, construction, or modification
4. Improve external prevention and enforcement systems
5. Improve emergency capability

Step 3 *Edit and review risk reduction measures:* The members of the steering committee were asked to review the list of risk reduction measures, to identify redundancies and errors, and to comment on the completeness, logical structure, and logical consistency of the listing. A revised list of 117 edited and corrected risk reduction measures was created by this process.

Step 4 *Group risk reduction measures by performance:* Before the risk reductions could be tested, they had to be converted to a form consistent with modeling parameters. The intended effects of the risk reduction measures on the system had to be identified before the appropriate modeling changes could be determined. A six-stage framework based on the concept of the causal chain, developed for maritime risk assessment by Harrald (1995) based on earlier work by Baisuck and Wallace (1977), was used as a basis for this reclassification of risk measures. As shown in Figure 4, risk interventions can affect the system by influencing stages in the causal chain in one or more of the following six ways:

1. Decrease frequency of root or basic cause events.
2. Decrease frequency of immediate cause (triggering) events.
3. Decrease exposure to hazardous situations.
4. Intervene to prevent an accident if an incident (error or failure in hazardous situation) occurs.
5. Reduce consequences (oil outflows in the PWS case) if an accident occurs.
6. Reduce the impact of consequences (ameliorate impact of oil spills in PWS risk assessment case).

Category 6, reducing the impact of an oil spill once it occurs, was beyond the scope the PWS risk assessment.

Step 5 *Identify risk measures in place in the base case, minimum safeguard case, and maximum safeguard case:* The risk measures currently in place were identified using system documentation (VTS Users Manual, VTS Operating Manual, Vessel Escort and Response Plan), regulations, and laws. Procedures followed by shippers, the Coast Guard, and Alyeska/SERVS not formally established were ascertained through interviews. Risk reduction measures that could not be changed from the base case without changing regulations or laws that applied nationally or internationally were identified by the contract team. A minimum safeguard case was established based on this analysis. Additional safeguards above the base case were defined in operational terms.

Step 6 *Relate performance measures to model parameters:* Evaluating risk reduction measures using the PWS risk assessment models (fault tree, system simulation, MARCS) required analysts to determine how the effect of each type of risk reduction measure could be represented in the language of one or more of the risk models.

Step 7 *Develop evaluation plan:* The evaluation plan was based on the concept, stated above, of using the hierarchical decomposition to ensure that critical areas were evaluated and valuable time was not allocated to evaluating marginal interventions. The assessment of the base case risk was the basis for all risk reduction evaluations. The risk reduction evaluation then proceeded in three phases:

1. In phase one of the risk reduction evaluation the system risks resulting from the minimum safeguard case and the maximum safeguard case were assessed. Comparing the base case results to the minimum and maximum cases provided a valuable assessment of the relative effectiveness of measures already in place in the baseline case.

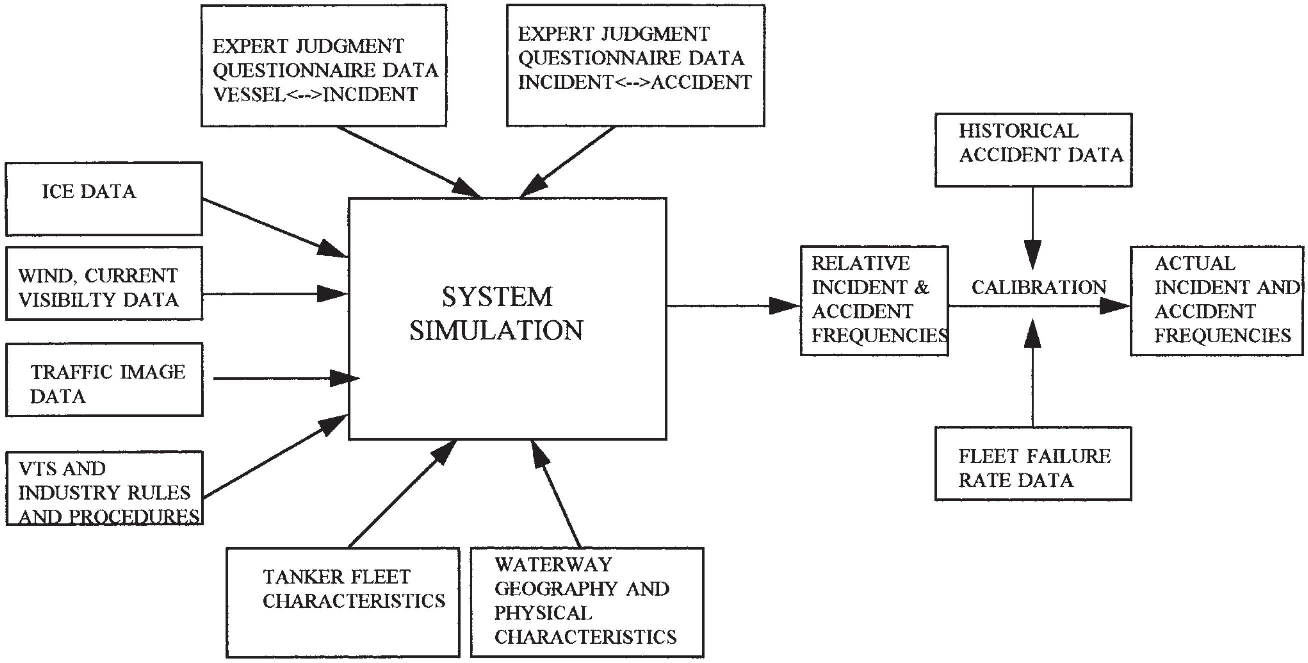

Figure 2. Flow chart showing system simulation inputs and outputs

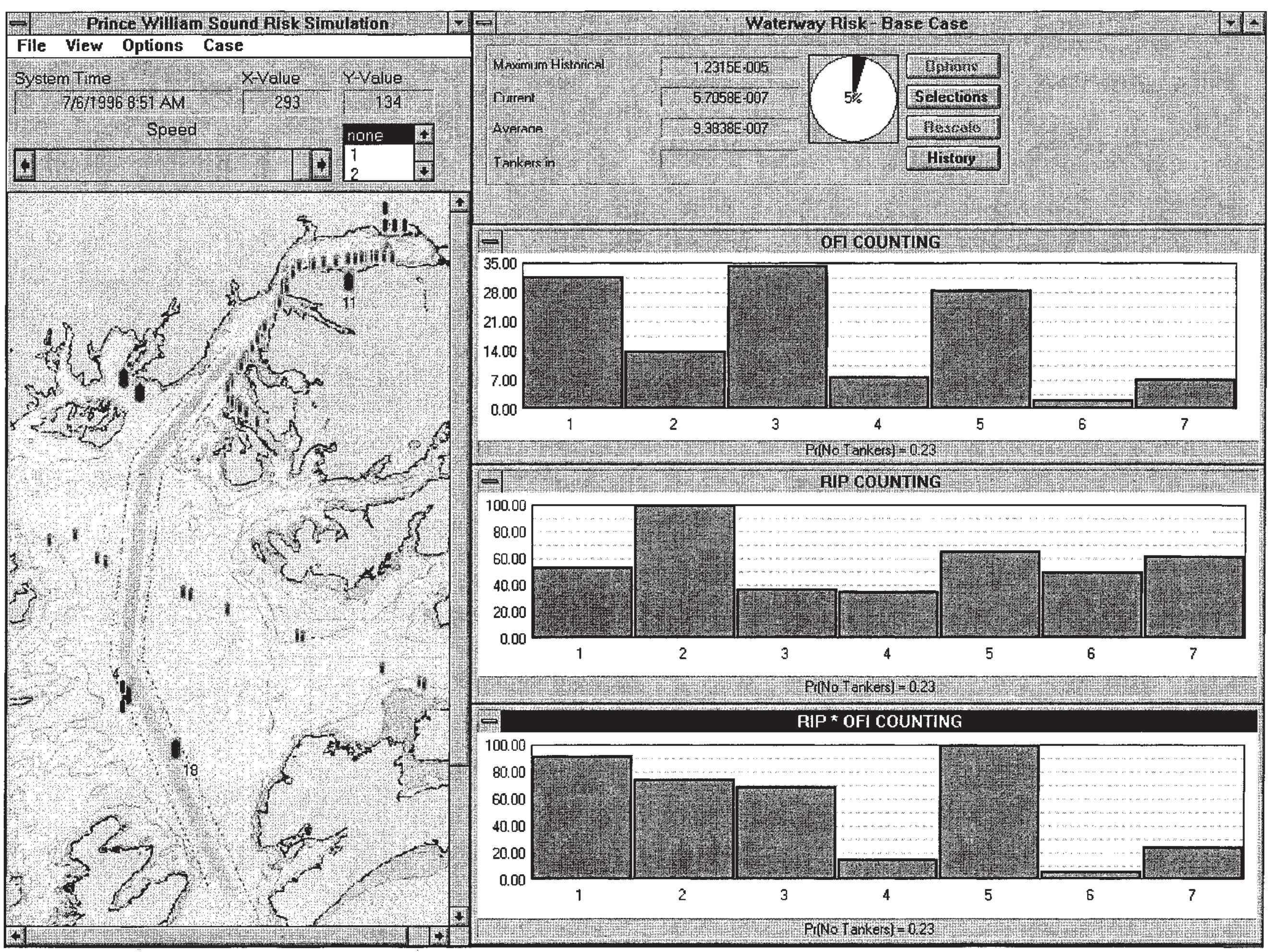

Figure 3. Screen print of PWS simulation in operation

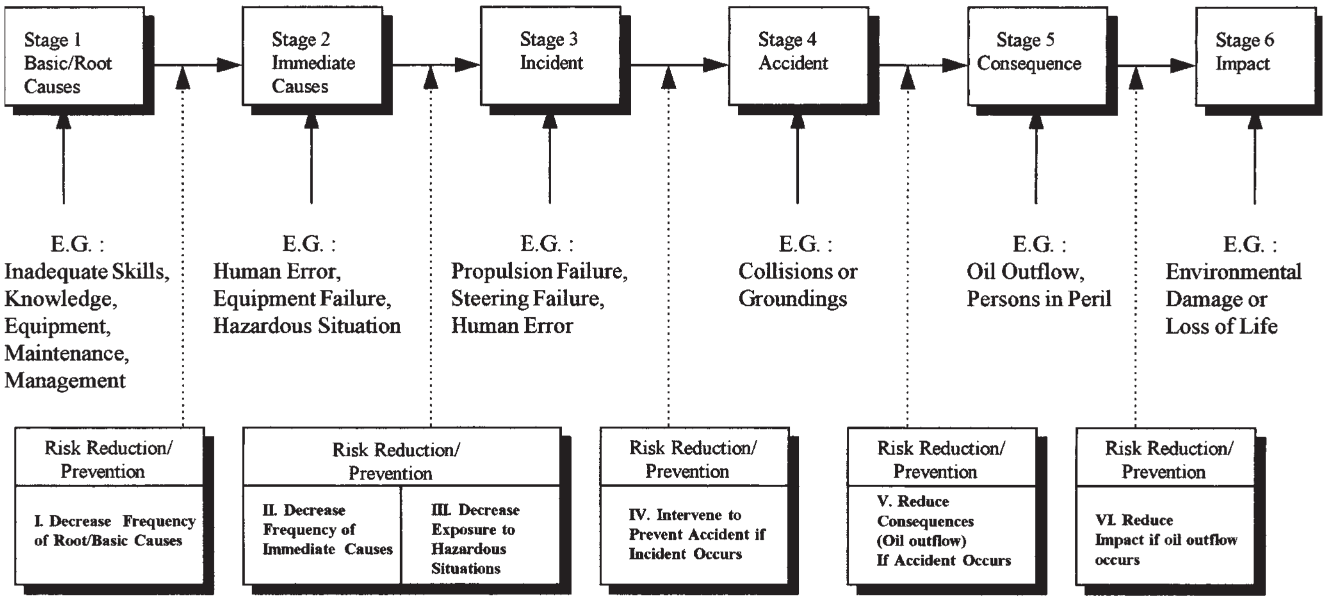

Figure 4. Framework for maritime risk assessment and risk reduction interventions

2. In phase two of the risk reduction evaluation, system risk when groups of measures represented by each of the five general categories listed in step 4 were implemented.
3. In phase 3 of the risk reductions, measure evaluation system risk when smaller changes are made to the system. The effects of the implementation of groups of measures composed of subgroups or types or individual risk reduction measures were assessed.

Step 8 *Produce risk reduction evaluation results:* The risk models were adapted, appropriate computer runs were performed, and results were obtained and risk reduction measures sorted by their anticipated risk reduction effect.

The sorted list risk reduction measures evaluated by one or more of the four models used in the PWS risk assessment will be contained in the results released by the Prince William Sound Risk Assessment Steering Committee. However, the dynamic simulation showed the following relationships:

- Current closure and escort rules reduce grounding risk but increase collision risk in the system. Alternatives that increase the number of escorts or increase the severity of closure conditions increase the risk in the system.
- A revised escort scheme that combines close escorting in high-risk areas with appropriate standby vessels in other areas reduces systemwide risk.
- Safety management systems that reduce vessel reliability failures and human and organizational errors significantly reduce system risk.

Conclusions

The movement of tankers through Prince William Sound is a complex and dynamic process. The risk potential in the system at any given time depends upon what ships are in the system and the situational conditions that exist at that time. The risk reduction measures currently in place address the most significant risks in the system (powered and drift grounding). These measures are effective but not optimal and did not account for unanticipated effects elsewhere in the system. The technique of system simulation provided a unique capability of modeling the dynamic interactions caused by existing and planned risk interventions. The simulation shows that actions that reduce risk in one part of the system can increase risk at other places and times. The ability to identify and to evaluate this risk tradeoff is essential to risk managers. Expert judgment calibrated by actual data, as used in the simulation model, provided extensive insight into system risk. The support of the organizations represented on the PWS risk assessment steering committee ensured access to maritime experts and extensive organizational data and will help to ensure that the results of this risk assessment are used to improve the safety of oil transportation in Prince William Sound.

Biography

John Harrald is the director of the Institute for Crisis and Disaster Management and a professor of engineering management at the George Washington University. He served as a USCG officer for 22 years.

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