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OPTIMIZING EMERGENCY SORTIES AND STORM EVASION PLANNING

by

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The optimization model introduced in this thesis generates an Emergency Sortie Plan that minimizes the time required to reach the recommended Hurricane Evasion Point, evacuates all seaworthy ships, most efficiently utilizes the available pilots and tugs, and observes necessary safety constraints on basin congestion, nested berthing, and tidal-restricted ships. In a test of the model using data for Naval Station Norfolk during Hurricane Andrew, the model evacuated the ships 40 minutes earlier than the actual 11 hour schedule. In only 22 minutes on a personal computer the model provided a realistic estimate of the minimum time required to complete an Emergency Sortie, based on known information, not educated guesses.

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Optimizing Emergency Sortie
and Storm Evasion Planning

by

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Submitted in partial fulfillment
of the requirements for the degree of

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ABSTRACT

This thesis develops an optimization model for scheduling sorties of surface ships and submarines that are required to plan for port evacuation during hurricane conditions. At present, Emergency Sortie Plans are prepared manually by the Port Operations schedulers and often do not utilize the limited pilot and tug resources most efficiently.

The optimization model introduced in this thesis generates an Emergency Sortie Plan that minimizes the time required to reach the recommended Hurricane Evasion Point, evacuates all seaworthy ships, most efficiently utilizes the available pilots and tugs, and observes necessary safety constraints on basin congestion, nested berthing, and tidal-restricted ships. In a test of the model using data for Naval Station Norfolk during Hurricane Andrew, the model evacuated the ships 40 minutes earlier than the actual 11 hour schedule. In only 22 minutes on a personal computer the model provided a realistic estimate of the minimum time required to complete an Emergency Sortie, based on known information, not educated guesses.

DISCLAIMER

The reader is cautioned that the computer program developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the program is free of computational and logical errors, it cannot be considered validated. Any application of this program without additional verification is at the risk of the user.

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EXECUTIVE SUMMARY

This thesis develops an optimization model for scheduling sorties of surface ships and submarines that are required to plan for a port evacuation during hurricane conditions. Sortie and evasion is necessary to avoid storm damage to naval vessels and piers. At present, Emergency Sortie Plans are prepared manually and often do not utilize the limited pilot and tug resources most efficiently, resulting in time delays.

The goal of this thesis is twofold. The first goal is to develop an optimization model to assist the Port Operations schedulers in drafting an Emergency Sortie Plan for the ships berthed at the Naval Station Norfolk, Virginia, when a hurricane threatens the Hampton Roads area. The model assigns each ship to a specific sortie time period, which (1) minimizes the time required to complete the sortie, (2) minimizes harbor congestion, and (3) most efficiently utilizes the harbor pilots and tugs.

The second goal is to utilize the results of the optimization model, plus the position of Chesapeake Light and the Oceanographer's recommended Transit and Hurricane Evasion Points to calculate the minimum time required to complete an Emergency Sortie and Storm Evasion at a specified transit speed. This provides a realistic and timely input to the

Senior Officer Present Afloat (SOPA) Hampton Roads for making the sortie/no sortie decision.

The optimization model is based on the following five assumptions:

(1) Each sortie time period represents 20 minutes of time.

(2) The pilot and tugs are assigned to each ship for two consecutive sortie time periods.

(3) Only one ship can sortie per basin (slip) per sortie time period.

(4) A maximum of two ships can be berthed in a nest. The outboard ship must sortie prior to the inboard ship.

(5) Tidal-restricted ships (CV/CVNs, LHAs, LHDs) are assigned a specific sortie time period based on the expected H-Hour and the preferred departure windows on the day of an Emergency Sortie.

Given the pier/berth assignment and the number of tugs required for each ship and the total number of pilots and tugs available to support the sortie, the optimization model minimizes the maximum number of sortie time periods required subject to the following six constraints:

(1) **Sortie Time Period.** This constraint identifies the latest sortie time period, which is then made as early as possible in the optimization.

(2) **Departure Requirement.** All ships will sortie once.

(3) **Pilot Limitation.** This ensures that the number of pilots assigned does not exceed the total number of pilots available.

(4) **Tug Limitation.** This ensures that the number of tugs assigned does not exceed the total number of tugs available.

(5) **Basin Limitation.** This ensures that at most one ship can sortie from each basin in each sortie time period.

(6) **Nest Limitation.** If two ships are berthed together in a nest, the outboard ship sorties prior to the inboard ship.

The model generates five outputs (1) a Distance Table of the nautical miles between Chesapeake Light, Transit Point Alfa, and the Hurricane Evasion Point; (2) a listing by sortie time period of the recommended sortie time period for each ship berthed at the Naval Station; (3) pilot requirements per sortie time period; (4) tug requirements per sortie time period; and (5) the time required in hours for all ships to complete an Emergency Sortie and Storm Evasion.

In a test of the model using data for Naval Station Norfolk during Hurricane Andrew, the model evacuated the ships 40 minutes earlier than the actual 11 hour schedule. The model generated this Emergency Sortie Plan in *only 22 minutes using a 386 personal computer vice a significantly longer period* using the current manual methods.

The goals of this thesis have been met. But, the most important result is that a *realistic estimate* of the minimum time required to complete an Emergency Sortie and Storm Evasion, *based on known information and dependable analysis, not educated guesses*, is now available to SOPA Hampton Roads.

This optimization model has the flexibility to evaluate alternate "what if" emergency sortie and storm evasion plans. This planning model could easily be adapted for other naval stations.

I. INTRODUCTION

When the *Hurricane Havens Handbook for the North Atlantic Ocean* was issued to the commands and ships of the United States Atlantic Fleet, the Commander-in-Chief, U.S. Atlantic Fleet (CINCLANTFLT) issued the following statement regarding tropical cyclones:

> Tropical cyclones can be a formidable and dangerous foe, both at sea and in port. Storm damage can degrade [the fleet's] ability to fight and may result in expensive repairs, not to mention the potential for personnel casualties. Prudent, early action by commanders and commanding officers in response to tropical warnings is essential. Deviation from standard and recommended hurricane tactics can be justified only by extreme operational necessity. Fleet capabilities must not be degraded due to casualties resulting from tropical storms and hurricanes. (CINCLANTFLT, 1982)

"The classical doctrine held by most mariners is that ocean-going ships should leave ports which are threatened by a hurricane." (Hurricane Havens Handbook, p. I-1) Despite this natural caution, ships continue to be damaged in port or after leaving port, as a result of encounters with tropical cyclones. This stems mainly from the relative unpredictability of tropical cyclone movement.

The *Hurricane Havens Handbook* provides an assessment of the relative risks of remaining in port or putting to sea for the major U.S. ports along the Atlantic and Gulf coasts. Each assessment was based on the history of hurricane encounters, the predictability of hurricane movement, the shelter and security of berths, and the speed of advance of tropical cyclones. (Hurricane Havens Handbook, pp. I-1 - I-3)

Tropical cyclones capable of maintaining sustained winds of hurricane force (64 knots or greater) are possible, although rare, at the harbors in the Hampton Roads area (Norfolk, Little Creek, Portsmouth, Newport News, and Yorktown, Virginia). This stems from the particular combination of Hampton Roads's high latitude and the orientation of the coastline, which provides protection from the more vigorous tropical cyclones. Nevertheless, none of the harbors in the Hampton Roads area are safe havens during hurricane force winds. (Hurricane Havens Handbook, p. II-1) However, "the nature of the coastline makes an early departure imperative if a real threat is imminent." (Hurricane Havens Handbook, 1982, p. II-22)

Although the harbors will provide protection and have provided safe anchorage for small ships during tropical storm conditions, the recommended course of action for frigate-size and larger ships is evasion at sea. (Hurricane Havens Handbook, 1982, p. II-22) Smaller vessels and those vessels disabled by engineering problems may seek shelter in the Norfolk Naval Shipyard or other locations along the southern branch of the Elizabeth River. Smaller ships may also make use of designated hurricane anchorages in Chesapeake Bay. A major drawback to the hurricane anchorage areas is that the land in the region is very flat; therefore, there are few radar targets to use in establishing accurate ship position. (Hurricane Havens Handbook, p. II-1)

The recommendations of the *Hurricane Havens Handbook* were validated and reinforced by what happen to the naval vessels at hurricane anchorages in the Chesapeake Bay, when Hurricane Gloria struck the Hampton Roads area in September 1985. Due to the close proximity of Gloria to Norfolk when the sortie decision was made, it was decided that the ships in port would proceed to hurricane anchorages instead of attempting to evade at sea. This resulted in several near collisions and many ships dragging their anchors and/or almost going aground.

A. PROBLEM SCOPE

The focus of this thesis is to estimate the minimum time required for the ships in port to sortie as quickly as possible and to assist the schedulers in determining an optimal Emergency Sortie Plan. The methods were developed using data from Naval Station Norfolk but can be applied to other naval stations.

1. Naval Station Norfolk

The Naval Station Norfolk, Virginia, is located on the eastern shore of Hampton Roads at Sewells Point. Hampton Roads is a natural roadstead of 25 square miles, which is formed by the confluence of the James, the Nansemond, and the Elizabeth Rivers. Hampton Roads is the center of the largest

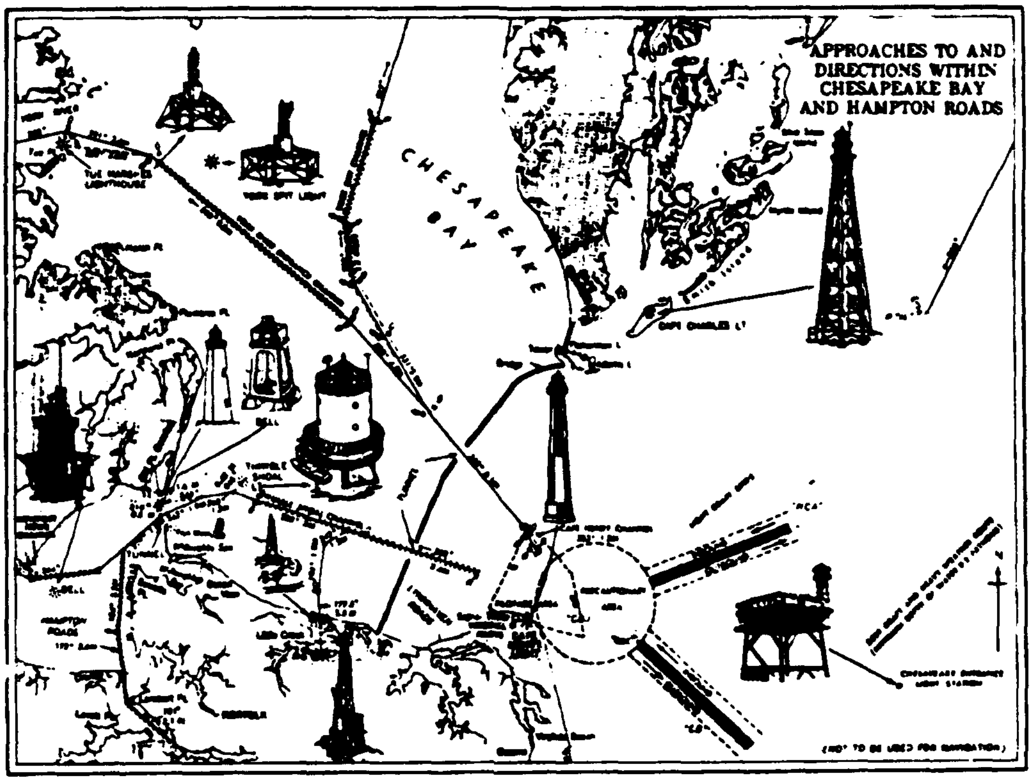

Figure 1.
Approaches to Chesapeake Bay and Hampton Roads

concentration of military and naval activities on the east coast of the United States. (Fleet Guide, 1991, p. 5-29)

The entrance of Hampton Roads lies between Old Point Comfort to the north and Fort Wool to the south. It is about 14.5 miles to the west of the entrance of Chesapeake Bay. The entrance of Chesapeake Bay lies between Cape Charles to the north, on the eastern shore of Virginia, and Cape Henry to the south. A deep water shipping channel, Thimble Shoal Channel, lying close to Cape Henry, connects Hampton Roads to the entrance of the Chesapeake Bay. (Fleet Guide, 1991 pp. 5-27)

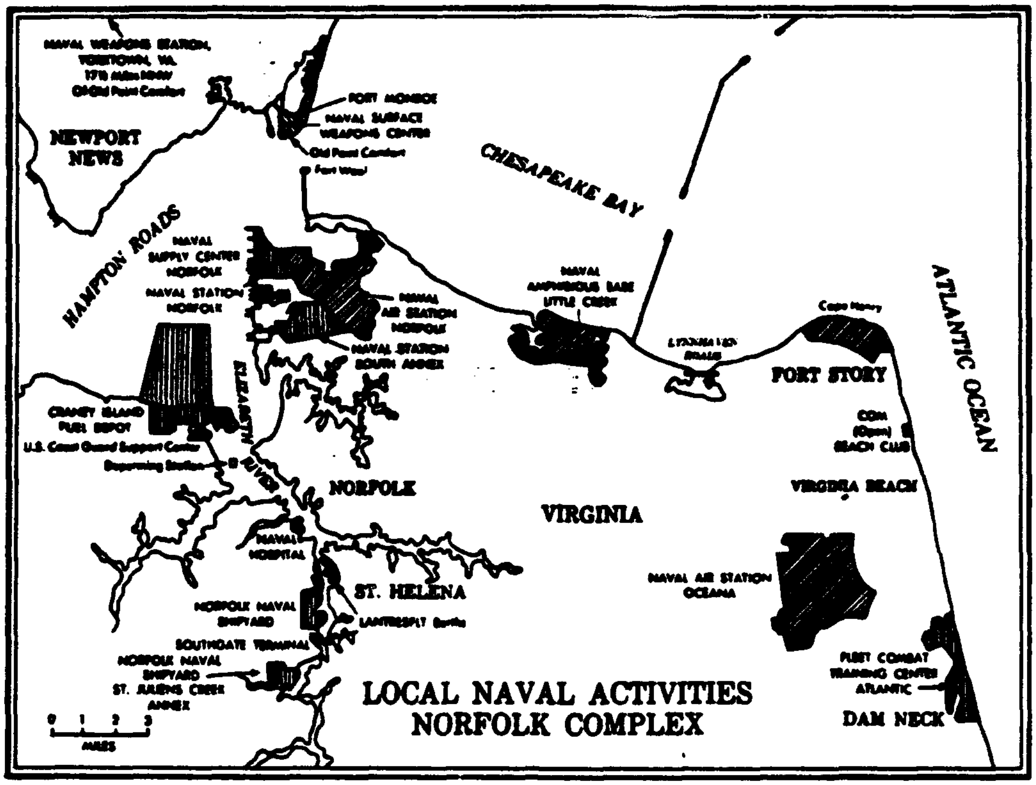

Figure 2.
Naval Activities in the Hampton Roads Area

Figure 1 shows the approaches to Chesapeake Bay and Hampton Roads, and Figure 2 depicts the naval activities in the Hampton Roads area.

Ships berthed at the Naval Station must transit Thimble Shoal Channel and a buoyed traffic lane, extending southeastward from Cape Henry, to reach the open waters of the Atlantic Ocean in the vicinity of Chesapeake Light (3654N - 07542W), a navigational aid marking the entrance to Chesapeake Bay for mariners. (Fleet Guide, 1991, p. 5-33)

The Naval Station consists of fourteen piers and 85 designated berths, depicted in Figure 3. At present, 97 ships are homeported at Norfolk. (USCINCLANT/CINCLANTFLT NOTICE 5440, 1991)

2. Emergency Sortie Considerations

Due to the inland location of the Naval Station, the geography of the Atlantic coastline of the United States, and the historical track of tropical cyclones in the North Atlantic; the timeliness of a sortie decision for the Hampton Roads area is essential. According to Commander, Second Fleet, the following time considerations are the critical factors in any sortie decision:

(1) Due to safety of navigation considerations a night sortie should be avoided. This has the potential to cause an *eight to twelve hour delay*.

(2) *Twelve to sixteen hours* would be required for all seaworthy ships to clear the Naval Station piers.

(3) Each ship requires approximately *three hours* to sortie from its assigned berth, transit Thimble Shoal Channel, and reach the open ocean in the vicinity of Chesapeake Light. See Note.

(4) Due to potential storm recurvature and inherent forecast error, ships will usually need to run nearly 200 miles to comfortably evade approaching tropical cyclones (*a thirteen hour transit at 15 knots*) and reach the recommended Hurricane Evasion Point. This transit will be in less than optimal sea states due to rapid swell propagation in advance of tropical cyclones. (Commander, Second Fleet, 1992)

Notes:
(1) Ships are limited to 10 knots from the Naval Station piers to Elizabeth River Buoy One and are limited to 15 knots between Elizabeth River Buoy One and Cape Henry. (Fleet Guide, 1991, p. 5-28)

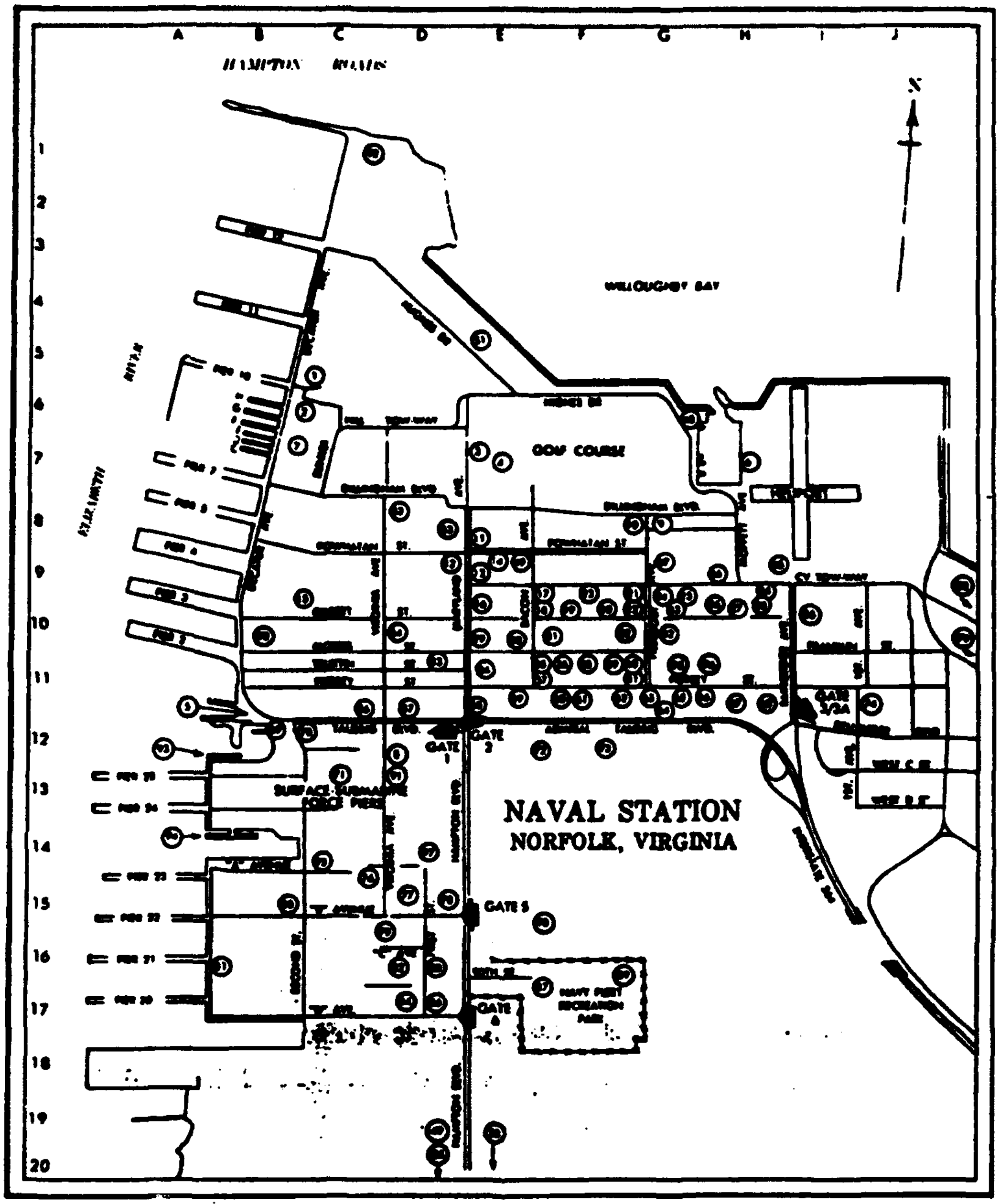

Figure 3.
Naval Station Norfolk, Virginia

Thus, once the decision to sortie has been made, the time required to complete an Emergency Sortie and to evade an approaching storm is approximately *36 to 44 hours.*

In August 1992 an Emergency Sortie Plan was issued for Hurricane Andrew, as a precaution, but was not implemented because Hurricane Andrew remained on a westerly course, striking southern Florida. This Emergency Sortie Plan is contained in Appendix A.

3. Senior Officer Present Afloat

The decision to sortie or to remain in port is made by the Senior Officer Present Afloat (SOPA) for the Hampton Roads Area. CINCLANTFLT exercises the command functions of SOPA Hampton Roads. To facilitate execution of SOPA responsibilities, the Hampton Roads area has been divided into five subareas. Table 1-1 shows the daily average number of ships present in each SOPA Subarea.

TABLE 1-1
DAILY AVERAGE NUMBER OF SHIPS PRESENT

SOPA Subarea	Ships Present
Norfolk	40-45
Portsmouth	20-25
Little Creek	10-15
Newport News	5-10
Yorktown	1

The ships berthed in the Portsmouth and Newport News SOPA Subareas are normally in scheduled maintenance availabilities at the Norfolk Naval Shipyard or at one of the private shipyards along the southern branch of the Elizabeth River or at the Newport News Shipbuilding & Drydock Company. As a result, these ships would not be able to sortie in the event of an Emergency Sortie. The ships berthed in the

Norfolk, Little Creek, and Yorktown SOPA Subareas, however, are normally in a 96 hour or less readiness for sea condition and would be able to conduct an Emergency Sortie.

It is readily apparent from the geographical location of the Naval Station and the large number of ships present that the Norfolk SOPA Subarea will required the most time to complete an Emergency Sortie.

B. CURRENT PROCEDURES

The Naval Station provides mandatory harbor pilot and tug boat services to all arriving and departing ships. The harbor pilot controls the movements of the tugs and assists the Commanding Officer of each ship in the mooring or unmooring evolution. The number of tugs assigned to each ship is dependent upon several factors. These factors include the class, maneuverability, draft, sail area, and designated berth of each ship; as well as, the wind, weather, current, and tidal conditions at the time of arrival or departure. An aircraft carrier (CV/CVN) normally requires seven tugs, large auxiliary ships (TAO, AFS, AOR) normally require four tugs, and cruisers (CG)/destroyers (DD/DDG) require two tugs. Appendix B contains a Nominal Tug Requirements Table listing the tug requirements by ship class. There are six harbor pilots and eight U.S. Navy tugs available to support ship movements at the Naval Station. (White, 1992) The large number of ships present with limited harbor pilot and tug resources combine to make sortie scheduling a difficult task requiring complex planning.

Sortie scheduling is further complicated by tidal-restricted ships. Due to the tidal currents at the Naval Station piers, the sortie times of aircraft carriers (CV/CVNs) and amphibious assault ships (LHAs and LHDs) are tidal restricted because of their deep draft, large sail area, maneuverability, and berth assignments. The preferred departure windows for the tidal-restricted ships are promulgated monthly by the Senior Harbor Pilot. The general rules for these departure windows are listed in Appendix B.

The Naval Station sortie plans are prepared manually by the Port Operations schedulers using a wall-size mock-up of the pier layout with scale-size ship silhouettes. Upon verifying the readiness for sea condition of the ships in port, the scheduler first determines how many harbor pilots and tugs are available. The Naval Station has contracts with several commercial towing companies; whereby, upon request and if available, the Naval Station can obtain up to ten additional tug boats.

After pilot and tug availability has been determined, the scheduler then determines the sortie time for the tidal-restricted ships based on the expected start time, or H-Hour, of an Emergency Sortie and the preferred departure windows for that day.

At this point, sortie scheduling becomes difficult. The scheduler assigns each ship to a sortie time based on each ship's berth and tug requirements, while trying to maximize the utilization of the available pilots and tugs and minimizing the congestion in the Elizabeth River and within the basins between the piers in order to expedite the movement of ships clear of the piers.

The sortie scheduling rationale is based on the following considerations:

(1) Each ship will require a pilot and tugs for approximately 40 minutes. This time includes the time required for the tugs to makeup to a ship, get the ship underway, debark the pilot, and proceed to their next assignment.

(2) If two ships are berthed in a nest, the ship berthed outboard must sortie prior to the inboard ship.

(3) Only one ship can sortie from a basin at a time.

Notes:
(1) A nest consists of two ships berthed together where one ship is berthed immediately outboard of a second ship, which is in turn berthed alongside of a pier.
(2) A basin is the water area between two adjacent piers.

The Emergency Sortie Plan also includes berthing instructions for ships that are unable to sortie due to main engine repairs or scheduled maintenance availabilities. When pilot and tug assets become available as an Emergency Sortie progresses, ships that remain in port are berth shifted to the most sheltered berths possible at the Naval Station or moved to the Norfolk Naval Shipyard.

When finalized, the Emergency Sortie Plan is transmitted to all ships and commands in the Hampton Roads area. Changes in the announced plan are inevitable. During a normal Monday morning sortie, the sortie schedule often changes hourly. The sheer frequency of revisions makes a strong case for the use of a computerized, optimizing sortie plan. The consequence of oversights is delay, which for an Emergency Sortie, may result in serious damage to ships and piers and in the potential for personnel casualties.

The following chapter reviews the linear integer program model formulation developed to met the thesis objectives. Chapter III is a review of a hypothetical evacuation problem, using data for the Naval Station Norfolk during Hurricane Andrew. Chapters IV and V summarize the computational results and the thesis conclusions.

The only previous related work on this subject was a Master's Thesis, *Optimal Ship Berthing Plans*, written by K.P. Thurman, which dealt with the scheduling of berth assignments and support services for surface vessels arriving at a Naval Station.

II. OPTIMIZING SORTIE PLANNING

The objective of this thesis is to develop an optimization model to assist the Port Operations schedulers in drafting an Emergency Sortie Plan for the ships berthed at the Naval Station Norfolk, Virginia, when a hurricane threatens the Hampton Roads area. The model should assign each ship to a specific sortie time, which (1) minimizes the time required to complete the sortie, (2) minimizes harbor congestion, (3) most efficiently utilizes harbor pilots and tugs, and (4) provides an estimate to the Senior Officer Present Afloat (SOPA) of the minimum time required to complete an Emergency Sortie and Storm Evasion. This chapter explains the basic model developed to satisfy these requirements.

The requirements call for a set of discrete ship-to-sortie-time-period assignments, with limitations on feasible assignments. These limitations depend on basins, pilots, tugs, and nested berthing. They are expressed as linear functions of the ship-to-sortie-time period assignment variables in a linear integer program.

A. LINEAR INTEGER PROGRAM MODEL FORMULATION

Assumptions:

(1) Each sortie time period represents 20 minutes of time.

(2) The pilot and tugs are assigned to each ship for two consecutive sortie time periods.

(3) Only one ship can sortie per basin (slip) per sortie time period.

(4) A maximum of two ships can be berthed in a nest. The outboard ship must sortie prior to the inboard ship.

(5) Tidal-restricted ships are assigned a specific sortie time period based on the expected H-Hour and the preferred departure windows on the day of an Emergency Sortie.

Indices:

b	-	berths
bs	-	basins
p	-	piers
s or ss	-	ships (hull number)
t or tt	-	sortie time periods

Given Data:

$ADJ_{s,ss}$ = 1 , if ship s is inboard of ship ss
= 0 , otherwise

$BELONG_{bs,p}$ = 1 , if pier p belongs to basin bs
= 0 , otherwise

$SB_{s,b}$ = 1 , if ship s is in berth b
= 0 , otherwise

$SP_{s,p}$ = 1 , if ship s is at pier p
= 0 , otherwise

$TUGS_s$ - number of tugs required for ship s

PAVAIL - total number of pilots available

TAVAIL - total number of tugs available

Derived Data:

$SHIPBASIN_{s,bs}$ = 1 , if ship s is in basin bs
= 0 , otherwise

Binary Variable:

X_{st} = 1 , if ship s assigned sortie time period t
= 0 , otherwise

Free Variable:

Z - Indicates the minimum number of sortie time periods t required to complete Emergency Sortie

Formulation:

Minimize Z

Subject to:

(1) $Z \geq \sum_{t} t * X_{st}, \quad \forall\, s$

(2) $\sum_{s} X_{st} * SHIPBASIN_{s,bs} \leq 1, \quad \forall\, bs, t$

(3) $\sum_{t} X_{st} = 1, \quad \forall\, s$

(4) $\sum_{s} X_{st} + \sum_{s} X_{s(t-1)} \leq PAVAIL, \quad \forall\, t$

(5) $\sum_{s} X_{s.} * TUGS_{s} + \sum_{s} X_{s(t-1)} * TUGS_{s} \leq TAVAIL, \quad \forall\, t$

(6) $X_{st} \leq \sum_{tt \ni (tt < t)} X_{sstt}, \quad \forall\, t, \quad \forall\, s, ss \ni (ADJ_{s,ss} = 1)$

In the above formulation, the objective function is to make the latest assigned sortie time period as early as possible.

Constraints (1) identify the latest assigned sortie time period. Constraints (2) require that at most one ship can sortie from each basin in each sortie time period. Constraints (3) ensure that each ship sorties once. Constraints (4) ensure that the number of pilots assigned does not exceed the total number of pilots available. Constraints (5) ensure that the number of tugs assigned does not exceed the total number of tugs available. Constraints (6) require that if two ships, ship s and ship ss, are berthed in a nest, then the outboard ship, ship ss, will sortie prior to the inboard ship, ship s.

The above model was generated and solved with the Naval Station Norfolk Hurricane Andrew data. The solution is discussed in the next two chapters.

B. REPORTS PROGRAM

Using the additional inputs of the latitude and longitude of the transit and evasion points--Chesapeake Light, Transit Point Alfa, and the recommended Hurricane Evasion Point; as well as, the value of the free variable Z, generated by the Linear Integer Program, the Reports Program calculates the Total Evasion Time.

Total Evasion Time is defined as the minimum time required for the last ship to sortie and reach the recommended

Hurricane Evasion Point via Chesapeake Light and Transit Point Alfa. This is calculated by

(1) converting the value of the free variable Z (the number of sortie time periods required) into time (in hours),

(2) adding the *3.0 hours* required to transit from the Naval Station piers to the vicinity of Chesapeake Light, and

(3) adding the time required to transit from Chesapeake Light to the recommend Hurricane Evasion Point via Transit Point Alfa at *fifteen knots*.

Once the Total Evasion Time has been calculated, five reports are generated by the Reports Program. The first report is a Distance Table of the nautical miles between Chesapeake Light, Transit Point Alfa, and the recommended Hurricane Evasion Point. The second report is a listing by sortie time period of the recommended sortie time period for each ship berthed at the Naval Station. The third and fourth reports outline the pilot and tug requirements by sortie time period. The fifth and final report is the model's output for Total Evasion Time (in hours), which is the minimum time required to complete the Emergency Sortie and Storm Evasion.

III. HYPOTHETICAL EVACUATION FOR HURRICANE ANDREW

A prototype model has been developed and evaluated using the GAMS generator (Brooke, Kendrick, and Meeraus, 1992) and XA solver (Sunset Software Technology, 1992). The model has been tested using the fifty-five ships berthed at the Naval Station on 23 August 1992, when an Emergency Sortie Plan was issued for Hurricane Andrew. An Emergency Sortie was not required because Hurricane Andrew remained on a westerly heading, striking southern Florida, but we can evaluate the model's solution and compare it to the plan that would have been used.

Berths at the Naval Station are numbered from inshore to seaward with odd numbers (one, three, and five) on the north side and even numbers (two, four, and six) on the south side. For this model these berths have been designated as B1 thru B6, and the outboard berths have been designated as the inboard berth number plus six or B7 thru B12. When a CV/CVN, LHA, LHD, or other large ship occupies the entire length of a pier, its berth is designated B0.

To simplify notation, piers with berths on both the north and south sides have been divided in two. For example, Pier 11 appears in the model as Pier 11N and Pier 11S. The notation "DDG995.10N.B7" means that USS SCOTT (DDG 995) is at

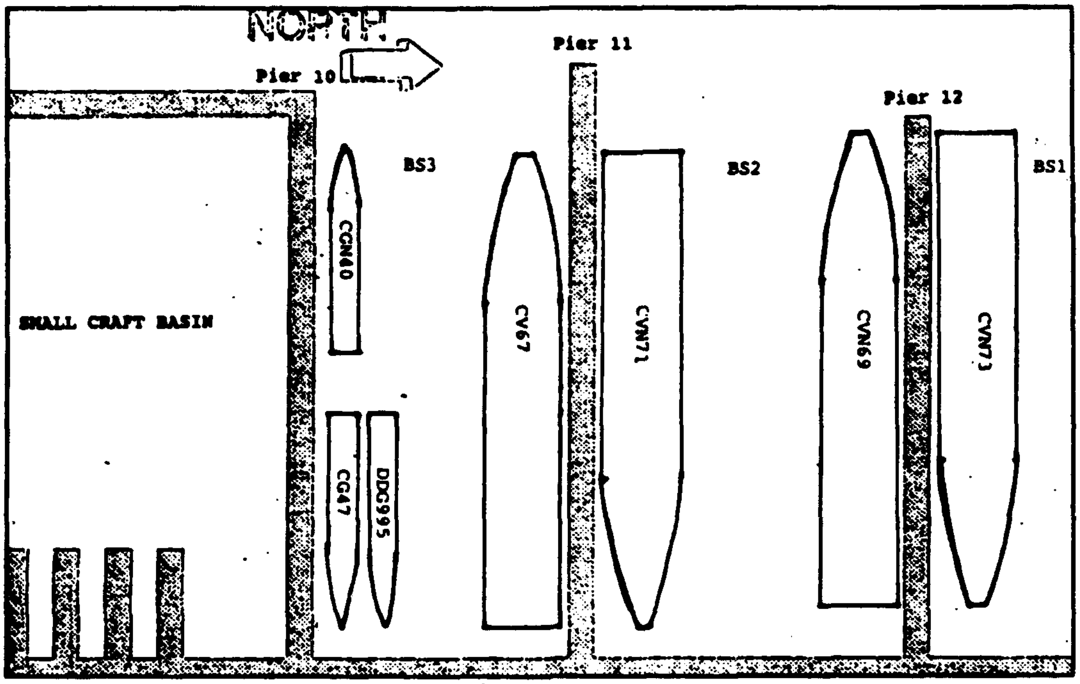

Figure 4.
Hurricane Andrew Berth Plan. Piers 10 thru 12.

Pier 10N/Berth 7, which is outboard of "CG47.10N.B1"--USS TICONDEROGA (CG 47) at Pier 10N/Berth 1.

It should be noted that the length of most U.S. Navy ships exceeds the length of the designated berths at the Naval Station. As a result, at most of the piers only two ships can be berthed pierside vice three, as indicated by the number of pierside berths at each pier.

The ships in this real world problem were distributed over twenty-eight piers and seventeen basins and included eleven two-ship nests. Additionally, this problem had a wide variety of ships types, including four aircraft carriers, three amphibious assault ships, and numerous cruisers, destroyers, amphibious ships, auxiliaries, and submarines.

The input data required for each ship includes the hull number, pier/berth assignment, and tug requirements. Table 3-1 displays the data required for the fifty-five ships in this problem. The basin and pier data for Naval Station Norfolk is listed in Table 3-2.

Figures 4 thru 7 depict the berthing assignments of the ships in port for this problem. To identify any particular ship or ship type, refer to *Jane's Fighting Ships*, 1992.

The total number of harbor pilots available (PAVAIL) was six, and the total number of tugs available (TAVAIL) was sixteen.

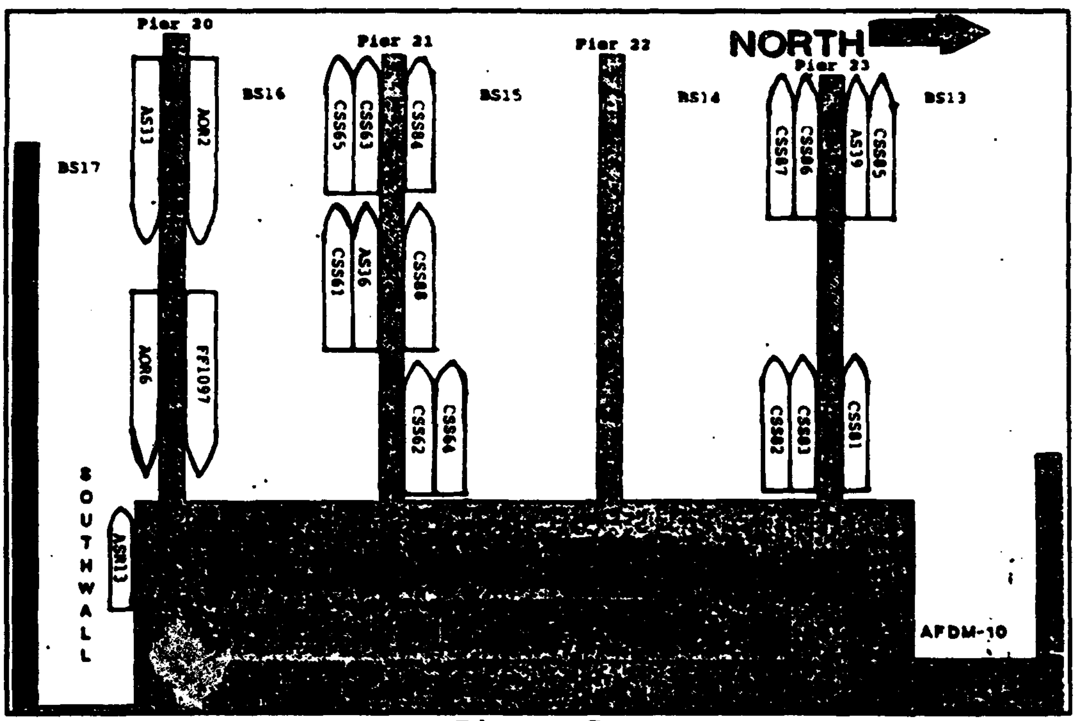

Figure 5.
Hurricane Andrew Berthing Plan.
Piers 20 thru 23 and Southwall.

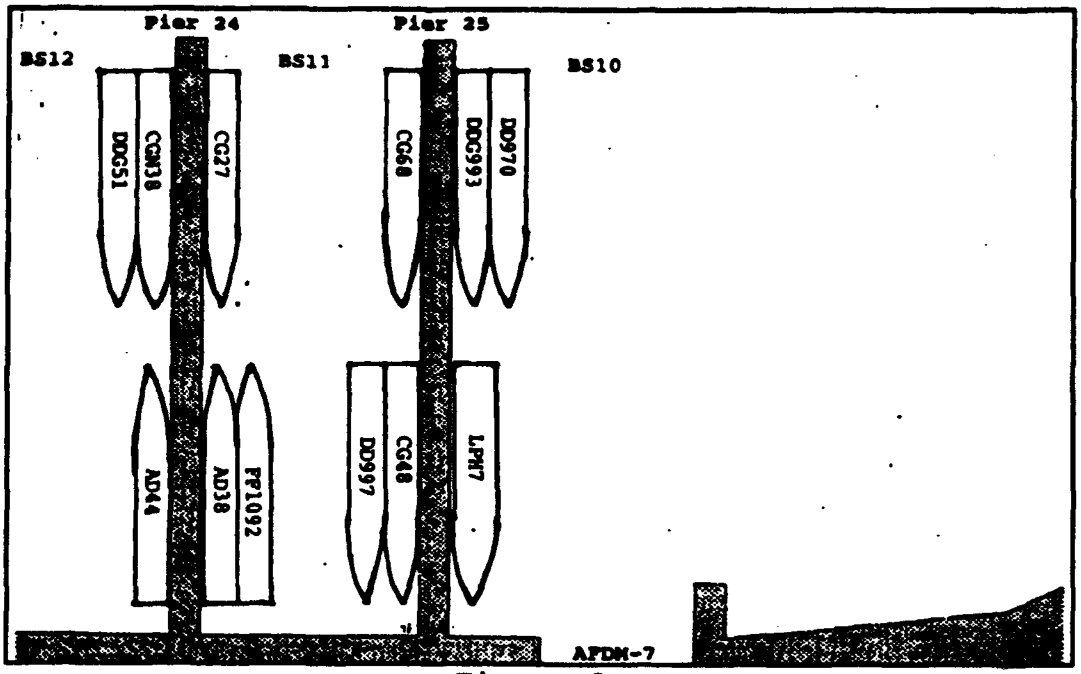

Figure 6.
Hurricane Andrew Berthing Plan. Piers 24 and 25.

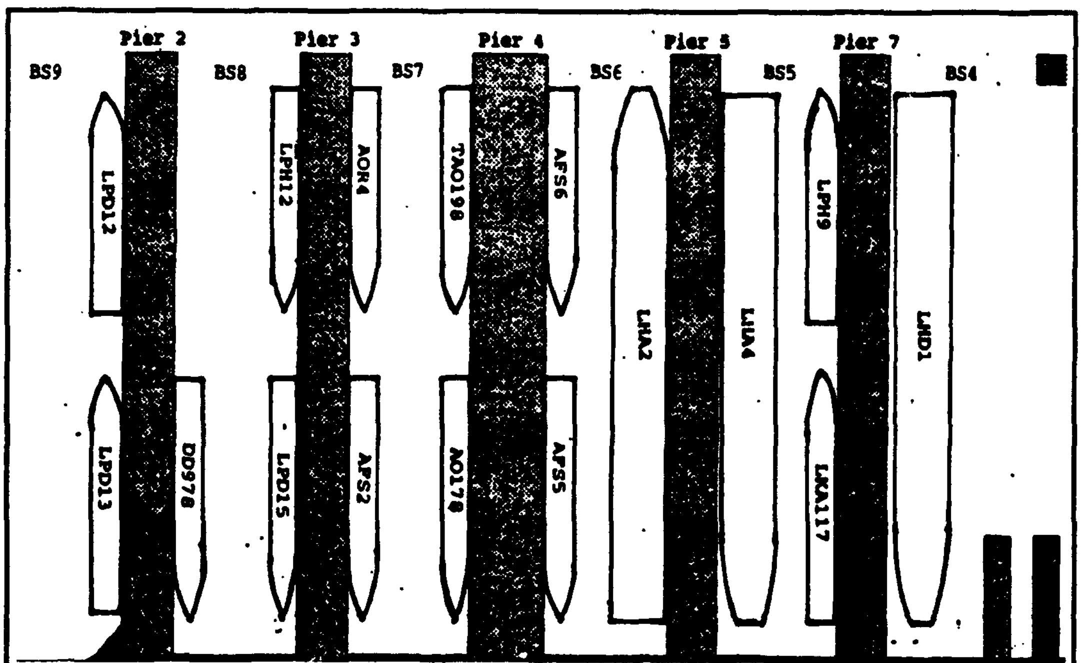

Figure 7.
Hurricane Andrew Berthing Plan. Piers 2 thru 7.

TABLE 3-1
HURRICANE ANDREW SHIP DATA

SHIP	PIER	BERTH	TUGS	
CGN40	10N	B5	2	
DDG995	10N	B7	2	
LPH9	7S	B6	4	
TAO198	4S	B6	4	
LKA117	7S	B2	3	
AFS6	4N	B5	3	
AOR4	3N	B5	4	
DD970	25N	B11	2	
AFS2	3N	B1	3	
LPH12	3S	B6	4	
LPD15	3S	B2	3	
DD978	2N	B1	2	
LPD13	2S	B2	3	
DDG993	25N	B5	2	
LPH7	25N	B1	4	
CG27	24N	B5	2	
CGN38	24S	B6	2	
DDG51	24S	B12	2	
CG68	25S	B6	2	
DD997	25S	B8	2	
AD44	24S	B2	4	
AOR2	20N	B5	4	
FF1097	20N	B1	2	
CG48	25S	B2	2	
AO178	4S	B2	4	
CVN73	12N	B0	7	(3)
LHD1	7N	B0	4	(3)
CVN71	11N	B0	7	(3)
CVN69	12S	B0	7	(3)
LPD12	2S	B6	3	
CG47	10N	B1	2	
AFS5	4N	B1	3	
LHA2	5S	B0	4	(3)
AD38	24N	B1	4	
LHA4	5N	B0	4	(3)
CV67	11S	B0	7	(3)
FF1092	24N	B7	2	
AOR6	20S	B2	4	
AS33	20S	B6	4	
CSS81	23N	B1	2	(1)
CSS82	23S	B8	2	(1)
CSS83	23S	B2	2	(1)
CSS61	21S	B10	2	(2)

TABLE 3-1 (Continued)
HURRICANE ANDREW SHIP DATA

SHIP	PIER	BERTH	TUGS	
CSS84	21N	B5	2	(1)
CSS85	23N	B11	2	(1)
CSS62	21N	B1	2	(2)
CSS63	21S	B6	2	(2)
CSS86	23S	B6	2	(1)
CSS87	23S	B12	2	(1)
CSS64	21N	B7	2	(2)
CSS65	21S	B12	2	(2)
CSS88	21N	B3	2	(1)
AS39	23N	B5	2	
AS36	21S	B4	2	
ASR13	WALL	B0	1	

Notes:
(1) Commander, Submarine Squadron EIGHT Units 1-8.
(2) Commander, Submarine Squadron SIX Units 1-5.
(3) Tidal-restricted ship.

TABLE 3-2
NAVAL STATION NORFOLK BASIN AND PIER DATA

BASIN	PIERS	BASIN	PIERS
BS1	12N	BS10	25N
BS2	12S, 11N	BS11	252, 24N
BS3	11S, 10N	BS12	24S
BS4	7N	BS13	23N
BS5	7S, 5N	BS14	23S, 22N
BS6	5S, 4N	BS15	22S, 21N
BS7	4S, 3N	BS16	21S, 20N
BS8	3S, 2N	BS17	20N, SOUTHWALL
BS9	2S		

The schedulers determine the tidal-restricted ships's sortie time period based on the expected H-Hour of an Emergency Sortie and the preferred Departure Windows for that day. Since the duration of most of the preferred Departure Windows is greater than one hour and with twenty minute sortie time periods, the schedulers have some flexibility in assigning tidal-restricted ships. However, when making these assignments, the schedulers must be careful not to violate the pilot, tug, and basin limitation constraints; otherwise the model will not be able to output a feasible solution.

An alternative to the scheduler making an arbitrary sortie time period assignment within the preferred Departure Windows would be to assign an upper bound of zero on the binary variable X_{st} for all sortie time periods outside of the preferred Departure Windows for each tidal-restricted ship. However, this procedure would increase the size of the model and the time required for the model to reach an integer solution. Since the movement of tidal-restricted ships is a major event for the Naval Station to support, the current procedure of assigning tidal-restricted ships to a specific sortie time period has been followed.

The inputs required for the seven tidal-restricted ships, four CV/CVNs and three LHA/LHDs, in this problem are shown in Table 3-3. The sortie time period assignments were taken from the Emergency Sortie/Berthing Plan issued for Hurricane Andrew.

TABLE 3-3
HURRICANE ANDREW TIDAL-RESTRICTED SHIPS

HULL NR	SORTIE TIME PERIOD
CVN73	T17
LHD1	T17
CVN71	T19
CVN69	T21
LHA2	T26
LHA4	T29
CV67	T32

The final input required is the latitude and longitude of Chesapeake Light, "CLT," and of the two recommended Transit and Evasion Points--Transit Point Alfa, "PTA," and Evasion Point, "PTE." Due to the nature of the coastline and the historical track of hurricanes (from south to north along the coast), it is necessary for ships from Norfolk attempting to evade an approaching storm to steam on an easterly course to gain sea room. Once across the path of the approaching storm, ships should change course to the southeast to take advantage of the likelihood that the hurricane will change heading and accelerate on a northeasterly track. Table 3-4 shows the Transit and Evasion Points used for this problem.

TABLE 3-4
HURRICANE ANDREW TRANSIT/EVASION POINTS

TRANSIT POINT	LAT-DEG	LAT-MIN	LONG-DEG	LONG-MIN
CLT	36	54	075	42
PTA	36	54	073	42
PTE	36	00	071	00

The model uses these points to calculate the Total Evasion Time, which is the minimum time required for the last ship to sortie and reach the recommended Hurricane Evasion Point via Chesapeake Light and Transit Point Alfa.

Table 3-5 contains the model output for recommended sortie times. If the H-Hour for the Hurricane Andrew Emergency Sortie was 0800 and using the recommended sortie times from Table 3-5, Port Operations would call away the pilots and tugs to get USS MILWAUKEE (AOR 2), USS KALAMAZOO (AOR 6), and CSS8

Unit 8 underway at 0800. USS INCHON (LPH 12) and USS JOSEPHUS DANIELS (CG 27) would sortie, starting at 0820. When the pilots and tugs assigned to the 0800 sortie group are released, they would proceed to the ships scheduled to sortie at 0840 and 0900. This process would continue until all ships scheduled to sortie have cleared the piers.

A review of Tables 3-6 and 3-7 indicates that both the Nest and Basin constraints have been satisfied - the outboard ship of each nest sorties prior to the inboard ship of that nest and at most one ship per basin sorties in each sortie time period. Additionally, each ship sorties once, which meets the requirements of the Departure constraint.

Tables 3-8 and 3-9 provide the Pilot and Tug Requirements for each sortie time period. A review of these tables indicates that the Pilot and Tug Availability constraints have been met. Additionally, Tables 3-8 and 3-9 show that if fewer tidal-restricted ships had been present, pilots and tugs were available to complete the Emergency Sortie earlier. Port Operations could use this information, the tug requirements per ship information from the input table, and the recommended sortie schedule to assign the pilots and tugs to individual ships.

The model output for distances in nautical miles between the Transit and Evasion Points and the Total Evasion Time in hours is shown in Tables 3-10 and 3-11. The information contained in these reports would enable Port Operations and the

TABLE 3-5
MODEL OUTPUT FOR RECOMMENDED SORTIE TIMES

SORTIE TIME PERIOD	HULL NR	PIER	BERTH	SORTIE TIME	
T1	AOR2	20N	B5	0000	
T1	AOR6	20S	B2	0000	
T1	CSS88	21N	B3	0000	(1)
T2	LPH12	3S	B6	+0020	
T2	CG27	24N	B5	+0020	
T3	AFS6	4N	B5	+0040	
T3	FF1097	20N	B1	+0040	
T4	CGN40	10N	B5	+0100	
T4	LPD12	2S	B6	+0100	
T4	AFS5	4N	B1	+0100	
T4	FF1092	24N	B7	+0100	
T5	AS33	20S	B6	+0120	
T5	CSS87	23S	B12	+0120	(1)
T6	DD997	25S	B8	+0140	
T6	CSS61	21S	B10	+0140	(2)
T6	CSS86	23S	B6	+0140	(1)
T7	DDG995	10N	B7	+0200	
T7	LPH9	7S	B6	+0200	
T7	AFS2	3N	B1	+0200	
T8	LKA117	7S	B2	+0220	
T8	DD970	25N	B11	+0220	
T8	CG47	10N	B1	+0220	
T9	AD38	24N	B1	+0240	
T9	CSS85	23N	B11	+0240	(1)
T9	CSS64	21N	B7	+0240	(2)
T10	AD44	24S	B2	+0300	
T10	AO178	4S	B2	+0300	
T11	LPH7	25N	B1	+0320	
T11	CSS84	21N	B5	+0320	(1)
T12	DDG51	24S	B12	+0340	
T12	CG48	25S	B2	+0340	
T12	CSS62	21N	B1	+0340	(2)
T13	TAO198	4S	B6	+0400	
T13	LPD13	2S	B2	+0400	
T14	AOR4	3N	B5	+0420	
T17	CVN73	12N	B0	+0520	(3)
T17	LHD1	7N	B0	+0520	(3)
T19	CVN71	11N	B0	+0600	(3)
T21	CVN69	12S	B0	+0640	(3)
T21	CSS82	23S	B8	+0640	(1)
T24	CSS83	23S	B2	+0740	(1)
T26	LHA2	5S	B0	+0820	(3)
T26	CSS81	23N	B1	+0820	(1)

TABLE 3-5 (Continued)
MODEL OUTPUT FOR RECOMMENDED SORTIE TIMES

SORTIE TIME PERIOD	HULL NR	PIER	BERTH	SORTIE TIME	
T26	CSS65	21S	B12	+0820	(2)
T27	AS39	23N	B5	+0840	
T29	LHA4	5N	B0	+0920	(3)
T30	LPD15	3S	B2	+0940	
T30	CGN38	24S	B6	+0940	
T30	CSS63	21S	B6	+0940	(2)
T32	DD978	2N	B1	+1020	
T32	DDG993	25N	B5	+1020	
T32	CG68	25S	B6	+1020	
T32	CV67	11S	B0	+1020	(3)
T32	AS36	21S	B4	+1020	
T32	ASR13	WALL	B0	+1020	

Notes:
(1) Commander, Submarine Squadron EIGHT Units 1-8.
(2) Commander, Submarine Squadron SIX Units 1-5.
(3) Tidal Restricted Ship.

TABLE 3-6
NEST CONSTRAINTS VERIFICATION

NEST	INBOARD SHIP	SORTIE TIME	OUTBOARD SHIP	SORTIE TIME
1	DDG993	T32/ +1020	DD970	T8 / +0220
2	CGN38	T30/ +0940	DDG51	T12/ +0340
3	CG48	T12/ +0340	DD997	T6 / +0140
4	CG47	T8 / +0220	DDG995	T7 / +0200
5	AD38	T9 / +0240	FF1092	T4 / +0100
6	CSS83	T24/ +0740	CSS82	T21/ +0640
7	AS36	T32/ +1020	CSS61	T6 / +0140
8	AS39	T27/ +0840	CSS85	T9 / +0240
9	CSS62	T12/ +0340	CSS64	T9 / +0240
10	CSS63	T30/ +0940	CSS65	T26/ +0820
11	CSS86	T6 / +0140	CSS87	T5 / +0120

TABLE 3-7
BASIN CONSTRAINTS VERIFICATION

SHIP	SORTIE TIME	SHIP	SORTIE TIME
	BASIN ONE		
CVN73	T17/ +0520		
	BASIN TWO		
CVN71	T19/ +0600	CVN69	T21/ +0640
	BASIN THREE		
CGN40	T4 / +0100	DDG995	T7 / +0200
CG47	T8 / +0220	CV67	T32/ +1020
	BASIN FOUR		
LHD1	T17/ +0520		
	BASIN FIVE		
LPH9	T7 / +0200	LKA117	T8 / +0220
LHA4	T29/ +0920		
	BASIN SIX		
AFS6	T3 / +0040	AFS5	T4 / +0100
LHA2	T26/ +0820		
	BASIN SEVEN		
AFS2	T7 / +0200	AO178	T10/ +0300
TAO198	T13/ +0400	AOR4	T14/ +0420
	BASIN EIGHT		
LPH12	T2 / +0020	LPD15	T30/ +0940
DD978	T32/ +1020		
	BASIN NINE		
LPD12	T4 / +0100	LPD13	T13/ +0400
	BASIN TEN		
DD970	T8 / +0220	LPH7	T11/ +0320
DDG993	T32/ +1020		
	BASIN ELEVEN		
CG27	T2 / +0020	FF1092	T4 / +0100
DD997	T6 / +0140	AD38	T9 / +0240
CG48	T12/ +0340	CG68	T32/ +1020
	BASIN TWELVE		
AD44	T10/ +0300	DDG51	T12/ +0340
CGN38	T30/ +0940		

TABLE 3-7 (Continued)
BASIN CONSTRAINTS VERIFICATION

SHIP	SORTIE TIME	SHIP	SORTIE TIME
	BASIN THIRTEEN		
CSS85	T9 / +0240	CSS81	T26/ +0820
AS39	T27/ +0840		
	BASIN FOURTEEN		
CSS87	T5 / +0120	CSS86	T6 / +0140
CSS82	T21/ +0640	CSS83	T24/ +0740
	BASIN FIFTEEN		
CSS88	T1 / +0000	CSS64	T9 / +0240
CSS84	T11/ +0320	CSS62	T12/ +0340
	BASIN SIXTEEN		
AOR2	T1 / +0000	FF1097	T3 / +0040
CSS61	T6 / +0140	CSS65	T26/ +0820
CSS63	T30/ +0940	AS36	T32/ +1020
	BASIN SEVENTEEN		
AOR6	T1 / +0000	AS33	T5 / +0120
ASR13	T32/ +1020		

Staff Oceanographers to provide a valuable and timely input to SOPA Hampton Roads for making the sortie/no sortie decision. More importantly, the Staff Oceanographers could quickly solve and answer various "what if" questions, using different Transit and Evasion Points based on different forecasts of the hurricane's movements.

If an Emergency Sortie commenced at 0800, it would require ten hours and twenty minutes for all fifty-five ships to clear the piers at the Naval Station. The last ship would sortie at approximately 1820 and would reach the Open Ocean in the vicinity of Chesapeake Light at 2120. The recommended storm evasion track is 272 nautical miles in length, 110 NM to Transit Point Alfa and an additional 162 NM to the recommended

TABLE 3-8
MODEL OUTPUT FOR PILOT REQUIREMENTS

SORTIE TIME PERIOD	PILOTS REQUIRED	SORTIE TIME PERIOD	PILOTS REQUIRED
T1	3	T17	2
T2	5	T18	2
T3	4	T19	1
T4	6	T20	1
T5	6	T21	2
T6	5	T22	2
T7	6	T23	0
T8	6	T24	1
T9	6	T25	1
T10	5	T26	3
T11	4	T27	4
T12	5	T28	1
T13	5	T29	1
T14	3	T30	4
T15	1	T31	3
T16	0	T32	6

TABLE 3-9
MODEL OUTPUT FOR TUG REQUIREMENTS

SORTIE TIME PERIOD	TUGS REQUIRED	SORTIE TIME PERIOD	TUGS REQUIRED
T1	10	T17	11
T2	16	T18	11
T3	11	T19	7
T4	15	T20	7
T5	16	T21	9
T6	12	T22	9
T7	15	T23	0
T8	16	T24	2
T9	15	T25	2
T10	16	T26	8
T11	14	T27	10
T12	12	T28	2
T13	13	T29	4
T14	11	T30	11
T15	4	T31	7
T16	0	T32	16

TABLE 3-10
MODEL OUTPUT FOR DISTANCES BETWEEN TRANSIT POINTS

	CLT	PTA	PTE
CLT		110.5	268.5
PTA	110.5		162.4
PTE	268.5	162.4	

TABLE 3-11
MODEL OUTPUT FOR TOTAL EVASION TIME

HOURS REQUIRED FOR SORTIE AND EVASION: 32

Evasion Point. This transit will require approximately eighteen hours to complete at fifteen knots. The Emergency Sortie and Evasion would be completed when the last ship reached the recommended Hurricane Evasion Point thirty-two hours after the Emergency Sortie commenced or at approximately 1520 the next day.

When the sortie times for each ship from the actual Emergency Sortie Plan for Hurricane Andrew were entered into the model, the solution was feasible. However, this plan required 34 sortie time periods (11 hours) to complete vice 32 sortie time periods (10 hours and 20 minutes). This was attributable to USS SIMON LAKE (AS 33) being assigned a sortie time of 1100 in the actual plan, which was forty minutes after the sortie time of the last tidal-restricted ship, USS JOHN F. KENNEDY (CV 67) at 1020. Pilot and tug availabilities in the actual plan could have supported an earlier sortie time for USS SIMON LAKE.

The most important result, however, was the fact that an Emergency Sortie Plan could be generated by the model in *only 22 minutes vice a significantly longer period*, using the current manual methods. Additionally, a *realistic estimate* of the minimum time required to complete an Emergency Sortie and Storm Evasion *based on defendable analysis, not educated guesses*, would be available to SOPA Hampton Roads.

IV. COMPUTATIONAL EXPERIENCE

GAMS, the General Algebraic Modeling System (Brooke, Kendrick, and Meeraus, 1992), "is designed to make the construction and solution of large and complex mathematical programming models more straightforward for programmers and more comprehensible to users of models." (Brooke, Kendrick, Meeraus, 1992, p. xii) GAMS has been developed to:

(1) Provide a high-level language for the compact representation of large and complex models;

(2) Allow changes to be made in model specifications simply and safely;

(3) Allow unambiguous statements of algebraic relationships;

(4) Permit model descriptions that are independent of solution algorithms. (Brooke, Kendrick, Meeraus, 1992, p. 3)

Using GAMS, to implement the prototype emergency sortie and storm evasion planning model enabled experimentation and easy changes to both the model and its data.

The Hurricane Andrew problem was originally run using both the ZOOM/XMP (Marsten and Singhal, 1990) and XA (Sunset Software Technology, 1992) solvers to debug the model.

The full-scale Hurricane Andrew problem, which included 28 piers, 164 berths, 17 basins, 55 ships, 11 nests, and seven tidal-restricted ships, created a linear integer programming model, consisting of 1,070 constraints and 1,760 binary variables and one free variable. It took GAMS 27 seconds to generate the model. A solution guaranteed to be within 20% of an optimal integer solution was achieved in 21:49 minutes, using the XA solver on a 386/33 based personal computer. The same model and solver achieved an integer solution in 4:18 minutes on a 486/33 based personal computer.

A time saving alternative was discovered when the outboard ships of the five nonsubmarine nests were assigned sortie time periods, in addition to the seven tidal-restricted ships. An integer solution was then achieved in 2:08 minutes. Since ships are only berthed in nests during periods of high port loading, it is recommended that the outboard ships of nonsubmarine nests, if any, and the tidal-restricted ships be pre-assigned a sortie time period.

The size of the Hurricane Andrew problem was mitigated by numerous restrictions on permissible realistic combinations of indices (basin, berths, ships, etc.). The dollar operator feature in GAMS "provides powerful and concise exception-handling capability." Explicit if-then-else statements constructed within an equation or assignment makes a program more manageable by decreasing the number of equations and variables generated. (Brooke, Kendrick, Meeraus, 1992, p. 72) The dollar operator was essential during the most difficult part of the model development, which was how to mathematically identify two ships, which were berthed in a nest.

The entire GAMS/XA input listing for the Hurricane Andrew problem is in Appendix C.

V. CONCLUSIONS

Optimization-based emergency sortie and storm evasion planning is feasible, effective, and most important timely. The prototype introduced and developed here gives compelling evidence that a computer-based model can express the emergency sortie and storm evasion planning problem concisely in easy-to-understand displays, and automatically produces face-valid emergency sortie plans capturing an enormous amount of the realism and detail that make such scheduling a challenging manual chore. More importantly, however, it provides a realistic estimate of the minimum time required to complete an Emergency Sortie and Storm Evasion, based on known information. Additionally, the method developed here encourages human interaction.

In the context of the proposed model, extensive user-friendly facilities can be accommodated to allow a port operations scheduler to assign any ship to a specific sortie time period. The optimization model then completes the tedious details of the Emergency Sortie Plan. Thus, the port operations scheduler can naturally express any "human judgement" issues and the optimization assures that high-quality emergency sortie plans are easily and quickly produced.

In a test of the model using data for Naval Station Norfolk during Hurricane Andrew, the model evacuated the ships 40 minutes earlier than the actual schedule. However, the most important result was that an Emergency Sortie Plan was generated by the model in *only 22 minutes vice a significantly longer period*, using the current manual methods. Additionally, a *realistic estimate* of the minimum time required to complete an Emergency Sortie and Storm Evasion, *based on known information, not educated guesses*, would be available to SOPA Hampton Roads.

This optimization program would also give the schedulers and the staff oceanographers the flexibility to evaluate alternate "what if" emergency sortie and storm evasion plans. In this role, quick-response identification of upcoming infeasibilities may be as useful as comparative evaluations of the relative merit of alternate plans. There is no current manual analog for this capability, nor is it likely that the manual time and effort will be available to devote much more than a cursory analysis of schedule changes or recommended transit and evasion point changes.

An optimization-based emergency sortie and storm evasion planning model provides a powerful decision aid to SOPA Hampton Roads, the port operations schedulers, and the staff oceanographers. This planning model could easily be adapted for other naval stations.

Emergency Sortie and Storm Evasion planning is crucial to the U.S. Navy. Considering the tempo of schedule changes, and the meticulous detail which preparation of every schedule must consider, a manual scheduler is hard-pressed to weigh myriad alternatives and fine-tune every alteration. It is inevitable that oversights will lead to delays. If an automatic, optimization-based decision support system prevents unnecessary delays and provides a realistic estimate of the minimum time required to avoid an approaching hurricane, then such a system clearly contributes to the readiness and safety of the fleet.

APPENDIX A

HAMPTON ROADS EMERGENCY SORTIE/BERTHING PLAN FOR HURRICANE ANDREW

Z P 231323Z AUG 92
FM NAVSTA NORFOLK VA//POO//
TO CTG ONE EIGHT THREE PT ONE
TG ONE EIGHT THREE PT ONE
INFO CINCLANTFLT NORFOLK VA//N31/N37//
COMNAVSURFLANT NORFOLK VA//N31//
COMNAVAIRLANT NORFOLK VA//N31/N32//
COMSUBLANT NORFOLK VA//N31/SWO//
COMSECONDFLT
COMCRUDESGRU TWO
COMPHIBGRU TWO
COMLOGGRU TWO
NAVEASTOCEANCEN NORFOLK VA//30//
SOPA ADMIN HAMPTON ROADS VA//N31//
SOPA ADMIN LITTLE CREEK SUBAREA VA//N3//
SOPA ADMIN PORTSMOUTH SUBAREA VA//100/200/300/330/800/NRRO//
SOPA ADMIN YORKTOWN SUBAREA VA//09C-3//
SOPA ADMIN NEWPORT NEWS SUBAREA VA//100/SWO//
CCGDFIVE PORTSMOUTH VA//JJJ//
COGARD MSO HAMPTON ROADS VA//JJJ//
COGARD MSC BALTIMORE MD//JJJ//
BT
UNCLAS //N03141//
SUBJ: HAMPTON ROADS EMERGENCY SORTIE/BERTHING PLAN
OPER/HURRICANE STORM ANDREW//
MSGID/GENADMIN/NAVSTA NORFOLK VA//POO//
REF/A/DOC/COMNAVBASENORVAHAMPINST 3141.1R CH-1/14MAY90//
AMPN/DESTRUCTIVE WEATHER PLAN//
RMKS/1. IAW REF A, THE FOLLOWING SORTIE/BERTHING PLAN IS ISSUED FOR HAMPTON ROADS SUBAREA. SHIPS ARE LISTED IN ORDER OF DEPARTURE IN THE EVENT SORTIE IS ORDERED. THIS INFORMATION IS PROVIDED FOR PLANNING PURPOSES ONLY AND IS NOT AN ORDER TO SORTIE:

SHIP	SORTIE TIME	CURRENT BERTH	BERTH/ANCHORAGE
GUNSTON HALL	0000	QUAY WALL EAST LCRK	SEA
MISSISSIPPI	+0020	10-5	SEA
SCOTT	+0020	10-1 O/B	SEA
GUAM	+0020	7-6	SEA
BIGHORN	+0020	4-6	SEA
EL PASO	+0020	7-2	SEA
PORTLAND	+0030	QUAL WALL DL LCRK	SEA
INDOMITABLE	+0100	18-NORTH LCRK	25
SAN DIEGO	+0100	4-5	SEA

SAN DIEGO	+0100	4-5	SEA
SAVANNAH	+0100	3-5	SEA
CARON	+0100	25-5	SEA
WORTHY	+0115	18-SOUTH LCRK	19
BOLD	+0130	17-NORTH LCRK	18
SYLVANIA	+0140	3-1	SEA
INCHON	+0140	3-6	SEA
PONCE	+0140	3-2	SEA
STUMP	+0140	2-1	SEA
RELENTLESS	+0145	17-NORTH LCRK	15
STALWART	+0200	17-SOUTH LCRK	14
BARNSTABLE COUNTY	+0215	16-SOUTH LCRK	SEA
NASHVILLE	+0220	2-2	SEA
KIDD	+0220	25-5	SEA
GUADALCANAL	+0220	25-1	SEA
JOSEPHUS DANIELS	INPT	24-5	24-5
VIRGINIA	+0220	24-6	SEA
ARLEIGH BURKE	INPT	24-6 O/B	SEA
FAIRFAX COUNTY	+0245	14-NORTH LCRK	SEA
ANZIO	+0300	25-6	SEA
HAYLER	+0300	25-2	SEA
SHENANDOAH	+0300	24-2	SEA
MILWAUKEE	+0300	20-5	SEA
MOINESTER	+0300	20-1	SEA
LA MOURE COUNTY	+0315	14-SOUTH LCRK	SEA
YORKTOWN	+0340	25-2	SEA
MONONGAHELA	+0340	C/I E/C	SEA
CSS8	+0340	23-1 S/F	SEA
CSS8	+0340	23-2 O/B S/F	SEA
BOULDER	+0345	13-NORTH LCRK	SEA
SUMTER	+0415	12-SOUTH LCRK	SEA
CSS8	+0420	23-2 S/F	SEA
CSS6	+0420	21-4 O/B	SEA
CSS8	+0420	21-5 S/F	SEA
CSS8	+0420	23-5 O/B S/F	SEA
CSS6	+0420	21-1 S/F	SEA
CSS6	+0420	21-6 S/F	SEA
EXPLOIT	+0430	11-SOUTH LCRK	NNSY
HOIST	+0445	57-EAST LCRK	SEA
GEORGE WASHINGTON	+0520	12 NORTH	SEA
WASP	+0520	7 NORTH	SEA
EMORY S LAND	+0520	23-5	SEA
THEODORE ROOSEVELT	+0600	11 NORTH	SEA
L Y SPEAR	+0600	21-4	SEA
DWIGHT D EISENHOWER	+0640	12 SOUTH	SEA
SHREVEPORT	+0720	2-6	2-1 (DPMA)
TICONDEROGA	INPT	10-1	3-6 S/F
CONCORD	INPT	4-1	3-2 S/F
SAIPAN	+0820	5 SOUTH	SEA
PUGET SOUND	INPT	24-1	3-1
KITTIWAKE	+0840	SOUTH WALL	SEA

NASSAU	+0920	5 NORTH	NNSY
JOHN F KENNEDY	+1020	11 SOUTH	SEA
EDENTON	INPT	19-NORTH LCRK	19-NORTH
FORTIFY	INPT	58-EAST LCRK	58-EAST
HARLAN COUNTY	INPT	13-SOUTH LCRK	12-SOUTH
THOMAS C HART	INPT	24-1 O/B	24-1
KALAMAZOO	AS DIR	20-1	SEA
JOSHUA HUMPHRIES	AS DIR	SEWELLS PT ANCH	SEA
SIMON LAKE	+1100	20-6	SEA
CSS8	INPT	23-6 S/F	23-6 S/F
OBREGON	AS DIR	LYNNHAVEN ANCH	SEA
CSS8	INPT	23-6 O/B S/F	23-6 O/B
CSS6	INPT	21-1 O/B S/F	21-1
CSS6	INPT	21-6 O/B S/F	21-6
CSS8	INPT	21-3	21-3
CSS8	INPT	24T	4-2
CSS8	INPT	DRYDOCK	DRYDOCK

2. REMARKS SPECIAL INSTRUCTIONS:

(A) SHIPS REMAINING INPORT LITTLE CREEK: USS EDENTON (ATS 1) SRA PIER 19N, USS FORTIFY (MSO 446) DECOM PIER 58E, USNS POWHATAN (TATF 166) MAIN ENG REPAIRS PIER 56E.

(B) IF SORTIE OCCURS AFTER 25 AUG USS NEWPORT WILL BE INPORT LITTLE CREEK AND WILL REMAIN INPORT AT PIER 56W.

(C) USS HARLAN COUNTY NEEDS 72HR NOTICE TO HAVE ONE SHAFT AVAIL.

BT

APPENDIX B

NAVAL STATION NORFOLK SORTIE SCHEDULING REQUIREMENTS

1. **HARBOR PILOT**. The Naval Station provides mandatory harbor pilot and tug boat services to all arriving and departing ships. The harbor pilot controls the movements of the tugs and assists the Commanding Officer of a ship in the mooring and unmooring evolution.

2. **TUGS**. The senior Harbor Pilot assigns tugs to assist each ship in the mooring/unmooring evolution. The number of tugs assigned to each ship is dependent upon several factors. These factors include the class, maneuverability, draft, sail area, and designated berth of each ship; as well as, the wind, weather, current, and tidal conditions at the time of arrival or departure. The following table list the nominal tug requirements by ship class:

NOMINAL TUG REQUIREMENTS

CLASS	TUGS
AD/AS	4
ASR/ARS	1
AOR	4
CG/CGN	2
CV/CVN	7
DD/DDG	2
FFG	1
LCC	4
LHA/LHD	4
LPH	4
LPD	3
LSD	3
LST	2
SSN	2
TAF/TAFS/AFS	3
TAO/AO	4

3. **TIDAL-RESTRICTED SHIPS**. Aircraft carriers (CV/CVNs) and amphibious assault ships (LHAs and LHDs) arrival and departure times are tidal restricted due to their deep draft, large sail area, maneuverability, and berth assignment; and the tidal currents at the Naval Station piers.

The preferred Departure Times/Windows for the tidal-restricted ships are promulgated monthly by the Senior Harbor Pilot. The general rules for these departure times/windows are outlined below:

a. **PIER 7N**. Due to the narrow gap between Pier 7N and the adjacent breakwater, the preferred departure time for a CV, LHA, or LHD is one hour before Slack Low Water or one hour before Slack High Water. This is a specific time NOT a window.

b. **NORTH SIDE OF ALL PIERS, EXCEPT PIER 7N**. The preferred departure time for a CV/CVN, LHA, or LHD is a window from one hour before Slack Low Current until Slack High Current.

c. **SOUTH SIDE OF ALL PIERS**. The preferred departure time for a CV/CVN, LHA, or LHD is a window from 1.5 hours after Slack Low Current until 1.5 hours before Slack High Current.

APPENDIX C

GAMS FORMULATION AND INPUT FOR HURRICANE ANDREW PROBLEM

```
$TITLE EMERGENCY SORTIE AND STORM EVASION PLANNING MODEL
$OFFUPPER $OFFSYMXREF $OFFSYMLIST $OFFUELXREF $INLINECOM { }

*------------------------------------------------------------
*                         INDICES
*------------------------------------------------------------

SETS
   B             berths
   BS            basins
   P             piers
   S             hull number of each ship
   T             sortie time period
   ;

   ALIAS(S, SS)
   ALIAS(T, TT)

$INCLUDE C:\GAMS386\NORVA\WORK.SET

SETS
B        / B0 * B12 /

BS       / BS1 * BS17 /

P        / 12N, 12S, 11N, 11S, 10N,
            7N, 7S, 5N, 5S,
            4N, 4S, 3N, 3S, 2N, 2S,
           25N, 25S, 24N, 24S,
           23N, 23S, 22N, 22S,
           21N, 21S, 20N, 20S, WALL /

S        / CGN40, DDG995, LPH9, TAO198, LKA117, AFS6, AOR4,
           DD970, AFS2, LPH12, LPD15, DD978, LPD13, DDG993,
           LPH7, CGN38, DDG51, CG68, DD997, AD44, AOR2, FF1097,
           CG48, AO178, CVN73, LHD1, CVN71, CVN69, LPD12, CG47,
           AFS5, LHA2, AD38, LHA4, CV67, FF1092, AOR6, AS33,
           CSS81, CSS82, CSS83, CSS61, CSS84, CSS85, CSS62,
           CSS63, CSS64, CSS65, CSS88, AS39, AS36, ASR13 /

T        / T1 * T32 /
;
```

```
SETS
   ADJ(S,SS)     yes if ship s is inboard of ship ss;

*------------------------------------------------------------
*                    GIVEN AND DERIVED DATA
*------------------------------------------------------------

PARAMETERS
   BELONG(BS,P)       1 if pier p belongs to basin bs
   BERTH(S,P,B,*)     input table for ship-pier-berth and tugs
   SHIPBASIN(S,BS)    1 if ship s is in basin bs
   TUGS(S)            tug requirements for each ship
   SB(S,B)            1 if ship s is in berth b
   SP(S,P)            1 if ship s is at pier p
   ;

SCALARS
   PAVAIL        total number of pilots available
   TAVAIL        total number of tugs available
   ;

$INCLUDE C:\GAMS386\NORVA\WORK.DAT

TABLE BERTH(S,P,B,*)  input table for ship-pier-berth and tugs

                          TRQMT
       CGN40 . 10N. B5      2
       DDG995. 10N. B7      2
       LPH9  .  7S. B6      4
       TAO198.  4S. B6      4
       LKA117.  7S. B2      3
       AFS6  .  4N. B5      3
       AOR4  .  3N. B5      4
       DD970 . 25N.B11      2
       AFS2  .  3N. B1      3
       LPH12 .  3S. B6      4
       LPD15 .  3S. B2      3
       DD978 .  2N. B1      2
       LPD13 .  2S. B2      3
       DDG993. 25N. B5      2
       LPH7  . 25N. B1      4
       CG27  . 24N. B5      2
       CGN38 . 24S. B6      2
       DDG51 . 24S.B12      2
       CG68  . 25S. B6      2
       DD997 . 25S. B8      2
       AD44  . 24S. B2      4
       AOR2  . 20N. B5      4
       FF1097. 20N. B1      2
       CG48  . 25S. B2      2
       AO178 .  4S. B2      4
       CVN73 . 12N. B0      7
```

```
        LHD1   .  7N. B0       4
        CVN71  . 11N. B0       7
        CVN69  . 12S. B0       7
        LPD12  .  2S. B6       3
        CG47   . 10N. B1       2
        AFS5   .  4N. B1       3
        LHA2   .  5S. B0       4
        AD38   . 24N. B1       4
        LHA4   .  5N. B0       4
        CV67   . 11S. B0       7
        FF1092. 24N. B7        2
        AOR6   . 20S. B2       4
        AS33   . 20S. B6       4
        CSS81  . 23N. B1       2
        CSS82  . 23S. B8       2
        CSS83  . 23S. B2       2
        CSS61  . 21S.B10       2
        CSS84  . 21N. B5       2
        CSS85  . 23N.B11       2
        CSS62  . 21N. B1       2
        CSS63  . 21S. B6       2
        CSS86  . 23S. B6       2
        CSS87  . 23S.B12       2
        CSS64  . 21N. B7       2
        CSS65  . 21S.B12       2
        CSS88  . 21N. B3       2
        AS39   . 23N. B5       2
        AS36   . 21S. B4       2
        ASR13  .WALL. B0       1
        ;

SCALARS
   PAVAIL                  /6/
   TAVAIL                 /16/
   ;

BELONG("BS1","12N")      = 1 ;
BELONG("BS2","12S")      = 1 ;
BELONG("BS2","11N")      = 1 ;
BELONG("BS3","11S")      = 1 ;
BELONG("BS3","10N")      = 1 ;
BELONG("BS4","7N")       = 1 ;
BELONG("BS5","7S")       = 1 ;
BELONG("BS5","5N")       = 1 ;
BELONG("BS6","5S")       = 1 ;
BELONG("BS6","4N")       = 1 ;
BELONG("BS7","4S")       = 1 ;
BELONG("BS7","3N")       = 1 ;
BELONG("BS8","3S")       = 1 ;
BELONG("BS8","2N")       = 1 ;
BELONG("BS9","2S")       = 1 ;
BELONG("BS10","25N")     = 1 ;
```

```
BELONG("BS11","25S")      = 1 ;
BELONG("BS11","24N")      = 1 ;
BELONG("BS12","24S")      = 1 ;
BELONG("BS13","23N")      = 1 ;
BELONG("BS14","23S")      = 1 ;
BELONG("BS14","22N")      = 1 ;
BELONG("BS15","22S")      = 1 ;
BELONG("BS15","21N")      = 1 ;
BELONG("BS16","21S")      = 1 ;
BELONG("BS16","20N")      = 1 ;
BELONG("BS17","20S")      = 1 ;
BELONG("BS17","WALL")     = 1 ;

    SHIPBASIN(S,BS) = 1 $(
        SUM( (P,B), BELONG(BS,P) * BERTH(S,P,B,"TRQMT") ) ) ;

    TUGS(S) = SUM( (P,B), BERTH(S,P,B,"TRQMT") ) ;

    SB(S,B) = 1 $( SUM( P, BERTH(S,P,B,"TRQMT") ) ) ;

    SP(S,P) = 1 $( SUM( B, BERTH(S,P,B,"TRQMT") ) ) ;

    LOOP( (S,SS) $( ORD(S) NE ORD(SS) ),
        LOOP( P $( SP(SS,P) + SP(S,P) EQ 2 ),
            ADJ(S,SS) = 1 $( SUM( B $( ( ORD(B) LE 7) AND
                            ( SB(SS,B+6) EQ 1 ) ), SB(S,B) ) )
        ) ;      {end p loop}
    ) ;          {end (s,ss) loop}

*------------------------------------------------------------
*                    DECISION VARIABLES
*------------------------------------------------------------

BINARY VARIABLE
   X(S,T)        1 if ship s assigned sortie time period t
   ;

$INCLUDE C:\GAMS386\NORVA\WORK.VAR

   X.LO("FF1092","T4")      = 1 ;
   X.LO("DD997","T6")       = 1 ;
   X.LO("DDG995","T7")      = 1 ;
   X.LO("DD970","T8")       = 1 ;
   X.LO("DDG51","T12")      = 1 ;

   X.LO("CVN73","T17")      = 1 ;
   X.LO("LHD1","T17")       = 1 ;
   X.LO("CVN71","T19")      = 1 ;
   X.LO("CVN69","T21")      = 1 ;
   X.LO("LHA2","T26")       = 1 ;
   X.LO("LHA4","T29")       = 1 ;
   X.LO("CV67","T32")       = 1 ;
```

```
FREE VARIABLE
   Z          minimum number of sortie time periods required
   ;

*-----------------------------------------------------------
*                       FORMULATION
*-----------------------------------------------------------

EQUATIONS

TOTAL(S)        minimum number of sortie time periods required

BLIMIT(T,BS)     one ship sorties per basin per time period

DLIMIT(S)        each ship sorties once

PLIMIT(T)        pilot limitation

TLIMIT(T)        tug limitation

NEST(S,SS,T)     outboard ship sorties prior to inboard ship

;

TOTAL(S)  ..                    {Objective Function}

    Z
=G=
    SUM( T, ORD(T) * X(S,T) )
    ;

BLIMIT(T,BS)  ..                {Basin Limitations}

    SUM( S, X(S,T) * SHIPBASIN(S,BS) )
=L=
    1
    ;

DLIMIT(S) ..                    {All ships sortie once}

    SUM( T, X(S,T) )
=E=
    1
    ;

PLIMIT(T)  ..                   {Pilot Limitations}

    SUM( S, X(S,T) )
+   SUM( S, X(S,T-1) )
=L=
    PAVAIL
    ;
```

```
TLIMIT(T)  ..                        {Tug Limitations}

    SUM( S, X(S,T) * TUGS(S) )
+   SUM( S, X(S,T-1) * TUGS(S) )
=L=
    TAVAIL
    ;

NEST(S,SS,T) $( ADJ(S,SS) ) ..    {Two-Ship Nest Constraint}

    X(S,T)
=L=
    SUM( TT $( ORD(TT) LT ORD(T) ), X(SS,TT) )
    ;

MODEL SORTIE /ALL/ ;
SOLVE SORTIE USING MIP MINIMIZING Z ;


*------------------------------------------------------------
*                     FOR REPORT WRITER
*------------------------------------------------------------

SETS
   A       transit and evasion points
   K       coordinates

   A       / CLT             Chesapeake Light
             PTA             Transit Point Alfa
             PTE             Evasion Point            /

   K       / X-AXIS, Y-AXIS, Z-AXIS /
   ;

   ALIAS(A, AA)

SCALARS
   PI      trigonometric constant          / 3.141592653 /
   R       radius of earth (miles)         / 3959 /
   ;

PARAMETERS
   LAT(A)         latitude angle (radians)
   LOC(A,*)       input table for transit and evasion points
   LONG(A)        longitude angle (radians)
   UK(A,K)        point in cartesian coordinates (unit sphere)
   USEG(A,AA)     straight line distance (unit sphere)
   UDIS(A,AA)     great circle distances (unit sphere)
   DIS(A,AA)      great circle distances (miles)
   ;
```

```
TABLE LOC(A,*)      input table for transit and evasion points

              LAT-DEG  LAT-MIN    LONG-DEG  LONG-MIN
    CLT         36       54         - 75      - 42
    PTA         36       54         - 73      - 42
    PTE         36       00         - 71      - 00
    ;                                          .

LAT(A)     =   ( LOC(A,"LAT-DEG") + LOC(A,"LAT-MIN") / 60 )
               * PI / 180 ;

LONG(A)    =   ( LOC(A,"LONG-DEG") + LOC(A,"LONG-MIN") / 60 )
               * PI / 180 ;

UK(A,"X-AXIS")  =  COS( LONG(A) )  *  COS( LAT(A) ) ;

UK(A,"Y-AXIS")  =  SIN( LONG(A) )  *  COS( LAT(A) ) ;

UK(A,"Z-AXIS")  =  SIN( LAT(A) ) ;

USEG(A,AA)  =  SQRT( SUM( K, SQR( UK(A,K) - UK(AA,K) ) ) ) ;

UDIS(A,AA)  =  PI ;

UDIS(A,AA) $( USEG(A,AA) LT 1.99999 )  = 2 * ARCTAN(
    USEG(A,AA) / 2 / SQRT( 1 - SQR( USEG(A,AA) / 2 ) ) ) ;

DIS(A,AA)  =  R * UDIS(A,AA) ;

*------------------------------------------------------------
*                            REPORTS
*------------------------------------------------------------

OPTIONS DIS:1 ;
DISPLAY DIS ;                    {Distance Table}

PARAMETER REP1(T,S,P,B)    Recommended Sortie Times (minutes)
;


REP1(T,S,P,B) $BERTH(S,P,B,"TRQMT")  =
   X.L(S,T) * ( ORD(T) - 1 ) * 20
   + ( X.L(S,T) * ORD(T) ) $( ORD(T) EQ 1)
   ;

OPTION REP1:0:0:1 ;
DISPLAY REP1 ;

PARAMETER REP2(T)      Pilot requirements for time t ;

REP2(T)  =  SUM( S, X.L(S,T) ) + SUM( S, X.L(S,T-1) ) ;
```

```
OPTION REP2:0:0:1 ;
DISPLAY REP2 ;

PARAMETER REP3(T)      Tug requirements for time t ;

REP3(T)   =   SUM( S, X.L(S,T) * TUGS(S) )
              + SUM( S, X.L(S,T-1) * TUGS(S) )
              ;

OPTION REP3:0:0:1 ;
DISPLAY REP3 ;

PARAMETER REP4         Hours required for Sortie and Evasion ;

REP4      =   ( (Z.L - 1) * 20/60 )
              + 3.0
              + ( DIS("CLT","PTA") / 15 )
              + ( DIS("PTA","PTE") / 15 )
              ;

OPTION REP4:0:0:1 ;
DISPLAY REP4 ;
```

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