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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

PREPOSITIONING FOR FLOODING IN THE SACRAMENTO REGION

by

Charles R. Farlow

March 2011

Thesis Advisor:	Javier Salmeron
Second Reaer:	David Alderson

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The Sacramento region is prone to flooding disasters. This thesis uses an optimization model to recommend where to preposition and/or expand warehouses, health-care personnel, ramp space, and transportation vehicle capacity. Adequate prepositioning helps evacuate the emergency population (EP), supply commodities to affected population (AP) that stays back in the affected areas (AAs), and transport other displaced population (DP) to the relief locations (RLs) for shelter. The goal is to minimize the expected number of EP and AP casualties, and then to maximize the DP transported to RL shelters, both during the first 72 hours after a flood disaster. We model a network of eight AAs and ten RLs, four flooding scenarios of different severity, and several budget levels for expansion of the initially prepositioned resources. We find that the RLs that the Federal Emergency Relief Agency (FEMA) has already selected have enough warehouse space to support the AP. This model recommends minor investment in additional health-care providers and emergency rescue vehicles for the EP. On the other hand, we observe a shortfall in mass housing capacity for the DP, even after fully expanding the capacity of existing facilities.

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PREPOSITIONING FOR FLOODING IN THE SACRAMENTO REGION

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

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ABSTRACT

The Sacramento region is prone to flooding disasters. This thesis uses an optimization model to recommend where to preposition and/or expand warehouses, health-care personnel, ramp space, and transportation vehicle capacity. Adequate prepositioning helps evacuate the emergency population (EP), supply commodities to affected population (AP) that stays back in the affected areas (AAs), and transport other displaced population (DP) to the relief locations (RLs) for shelter. The goal is to minimize the expected number of EP and AP casualties, and then to maximize the DP transported to RL shelters, both during the first 72 hours after a flood disaster. We model a network of eight AAs and ten RLs, four flooding scenarios of different severity, and several budget levels for expansion of the initially prepositioned resources. We find that the RLs that the Federal Emergency Relief Agency (FEMA) has already selected have enough warehouse space to support the AP. This model recommends minor investment in additional health-care providers and emergency rescue vehicles for the EP. On the other hand, we observe a shortfall in mass housing capacity for the DP, even after fully expanding the capacity of existing facilities.

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LIST OF ACRONYMS AND ABBREVIATIONS

AA, AAn	Affected Area, nth Affected area
AP	Affected Population
AFB	Air Force Base
AIRNAV	Airport Navigation
ARkStorm	Atmospheric River 1000 Storm
AST	Ambulance Strike Teams
C130, C17	Air Force aircraft (used in carrying cargo)
Cal EMA	California Emergency Management
CALEXPO	California Exposition Center
CALFIRE	California Fire Department
CDCR	California Department of Corrections and Rehabilitations
CDPH	California Department of Public Health
CDWR	California Department of Water Resources
CHP	California Highway Patrol
CPLEX	Optimization Software
DP	Displaced Population
EP	Emergency Population
FEMA	Federal Emergency Management Association
ft^3	Cubic Feet
GAMS	General Algebraic Modeling System
HC130	Coast Guard aircraft (used in rescue operations)
HMMWV	High Multipurpose Mobility Wheeled Vehicle
MFH	Mobile Field Hospital
MoT	Means of Transportation
POM	Prepositioning Optimization Model
RL, RLn	Relief Location, nth Relief Location
UH1H	Rescue Helicopter (Used by California Fire Departments)
USGS	United States Geological Survey

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EXECUTIVE SUMMARY

The Sacramento region is prone to flooding disasters. Although the Sacramento regional authorities and emergency management agencies have been planning in order to control and divert the water flow as much as possible, they also need to prepare emergency assets and personnel for cases where flooding is inevitable. A detailed analysis of the prepositioning of strategic resources before the disaster and its effect on the disaster's aftermath has not been performed. This prepositioning must occur well-in-advance of a disaster. That phase of the plan is important because the efficiency of subsequent logistics (such as the distribution of supplies to affected areas during the disaster) is conditioned by those strategic decisions.

This thesis uses a prepositioning optimization model (POM) to represent and analyze the above problem in the Sacramento region. We model a network of eight affected areas (AAs) and ten relief locations (RLs). The RLs have prepositioned resources and shelter. Some RLs also have airstrips for air transportation, and medical facilities. The AAs are locations that could be affected by a disaster. The population in these AAs are people that do not successfully evacuate prior to the disaster, and we separate them into three categories dependent on their needs: The first category is the emergency population (EP), who are the injured and/or in need of emergency evacuation to a facility that can administer medical assistance. The second category of population is the affected population (AP), who can stay in the AA, but need resources to be delivered in order to survive. The last population is the displaced population (DP), who will need to be transported to a RL for emergency shelter. Each AA has a certain number of each of these three populations in any given scenario. AAs can receive supplies via land or air, depending on their characteristics. The POM recommends where to preposition and/or expand warehouses, health-care personnel, ramp space and transportation vehicle capacity in order to help evacuate the EP, supply resources to the AP, and transport the DP during the first 72 hours after a flood disaster. The POM's main objective is to minimize the expected number of EP and AP casualties. As a secondary objective, the POM maximizes the DP transported to RL shelters.

Flooding disasters can cause different damage depending on their location and severity. In this thesis we evaluate four possible scenarios, from a mild flooding to more severe ones where air strips and roads may be impeded or even unavailable. Each scenario has different numbers of EP, AP and DP, calculated as different percentages of the population of the AA, depending on the scenario. We also analyze several budget levels for expansion of the initially prepositioned resources.

With the data and assumptions in this thesis, the POM finds that the RLs the Federal Emergency Relief Agency has already selected have enough warehouse space to support the AP in the flooding scenarios assumed in this thesis. Only when the existing warehouse capacity is hypothesized much lower than in our baseline assumption, expansion is recommended. Also, with a minor investment in additional health-care providers and emergency rescue vehicles, all the EP can be rescued and transported to medical facilities for treatment.

Additional insights gained from our analysis include the lack of mass housing for the DP. Even if the budget permits the maximum expansions of existing facilities, some DP would still not have shelter. This suggests that other space at hotels or additional RLs must be designated and included at the planning level.

According to the data gathered for this thesis, existing ramp space at the AAs is sufficient to offload the commodities delivered by aircraft, and does not need to be expanded. Depending on the scenario, a modest number of additional transportation vehicles are also recommended.

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I would like to thank my thesis advisor, Professor Javier Salmeron for his help in forming and writing this thesis. After countless hours of meetings, he provided me with the knowledge to understand the Prepositioning Optimization Model (POM) and how to manipulate it. Thank you for the numerous revisions of the thesis that continued to improve its organization and quality. I would like to thank Professor Javier Salmeron and Professor Aruna Apte for developing the POM, which was the basis of this thesis.

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I. INTRODUCTION

A. BACKGROUND

California is a state prone to many natural disasters such as earthquakes, fires, and floods. In the Sacramento region, flooding is the main concern (KCRA, 2005) because all the water flow from the Sierra Nevada Mountains is funneled through the region.

When Sacramento was originally settled in the 1840s, the proximity of the American and Sacramento rivers was seen as a great asset for the settlement, disregarding to a large extent the risk of possible massive flooding in the area. Levees were built to hold back the water; however, after heavy rainfall in early 1862, one of the levees failed and flooded the city. It has been a constant struggle of man versus nature ever since to prevent the recurring floods.

Currently, there are 1,115 miles of levees, of which 385 miles are under federal control, and the rest are financed and repaired by local jurisdictions (California Department of Water Resources [CDWR], 2010). For example, in February 24, 2006, Governor Arnold Schwarzenegger declared a state of emergency for the levees in the Sacramento River basin (Federal Emergency Management Association [FEMA], 2006). He identified 24 critical erosion sites along the levees that needed emergency repair. Because of this heterogeneous system, in some cases, levees are not repaired at critical points due to local financial problems. Over time, these levees have shrunk due to settling and erosion. The land behind them is sometimes 10 to 15 feet below sea level. Any break in the levee system can have a catastrophic effect on the Sacramento region (National Aeronautics and Space Administration, 2004).

Dams have also been built in order to mitigate the flood risk. In 1956, Folsom Dam was built on the lower American River. At the time, it was rated as a protection from a 500-year flood (Sacramento Area Flood Control Agency, 2010), but only 30 years later the winter storms dumped enough water into the river to overwhelm the dam and cause major flooding. The Folsom Dam was then improved, but in 1997 it was overwhelmed again. This flood is still fresh in the minds of local residents: Dozens of levees failed, nine people were killed, and 120,000 people were evacuated. Major interstate highways like I-5N and I-5S were closed, and relief efforts were disorganized. Over $2 billion in damages devastated the community for years after the waters had receded. Many emergency response workers look at this recent flood as a gauge to prepare for the next one. In an even more pessimistic scenario, a flood like the one in 1862 would cost an estimated $1 trillion in losses (United States Geological Survey [USGS], 2011).

The Sacramento regional authorities continue to work to control and divert the water flow as much as possible. However, they also need to prepare emergency assets and personnel for cases where flooding is inevitable.

B. CURRENT EMERGENCY PLANNING

The State of California has tasked each county to devise an individual emergency plan to respond to floods. Each county plan designates: (a) how the California Highway Patrol (CHP) will set up local evacuation, control and assistance points to assist in evacuation, (b) how the CDWR will watch and regulate the flow on the rivers, and (c) how the California Fire Department (CALFIRE) will assist in rescue and repair operations. These plans (Chairman Board of Supervisors Sacramento County, 2008) contain little detail as to where food, water, and medical supplies will originate, and how they will be delivered to those in need. They are also vague in where to transport the estimated 8% of the population that does not have a vehicle (FEMA, 2006). In a large disaster, multiple counties will be affected, so a unified coordination effort is needed.

The California Emergency Management Agency (Cal EMA) was established in January 2009, merging the power and responsibility of the Governor’s Office of Emergency Services and the Governor’s Office of Homeland Security (Cal EMA, 2010). The Cal EMA is in charge of preparing for and dealing with a disaster at regional and state levels. The California Disaster and Civil Defense Master Mutual Aid Agreement has enabled the counties to work together and support other counties when natural disasters happen (Office of Emergency Services, 1950). Cal EMA coordinates with the counties to provide mutual aid when needed. This has shown great success when dealing with large wildfires, where fire departments from all over the state provide the help to the county in need.

One of the regions with a major concern for flooding is California Mutual Aid Region IV, which includes Sacramento, Yolo, and nine other counties. Cal EMA tasks each county to devise a plan on how to preposition resources to provide basic food, water, medical supplies, and shelter if the disaster happens in their jurisdiction. As part of that planning, every year Cal EMA conducts a full-scale exercise called “Golden Guardian” (Cal EMA, 2011). During the exercise, Cal EMA devises an evacuation and relief plan for a disaster scenario and tests its execution. The scenario for Golden Guardian 2011 involves a large flood in the Sacramento-San Joaquin Delta Region. The counties and local agencies have submitted requests on how they want to participate in the Golden Guardian 2011 event, so the disaster scenario is not necessarily all-encompassing or uniform across all counties. For example, some counties request to participate in the event during the first two days of the hypothetical flooding, which posits the flood water encroached into their area, but not during the third day where the flooding reaches catastrophic level. Other counties have requested the simulated flood waters be at a lower level than assumed for the scenario, which flexes their response teams at a minor flood stage level. This leads to inconsistencies in the simulated exercise, like water flow at one location being well past flood stage while a short distance downstream it may be below flood stage.

FEMA has identified Sacramento as a major flood risk and has designated specific military bases and county fairgrounds as acceptable locations to establish centers for distribution and mass housing (FEMA, 2006). They completed an assessment of the locations by evaluating their warehouse storage capacity, helicopter pads and runway space, and potential for mass housing. Using this information, they have predesignated locations from which to send resources, and vehicles for their distribution, in preparation for a disaster. Mass housing sites can also be established at these locations.

Even though the potential for a large flood in the Sacramento region has been discussed extensively by FEMA, Cal EMA, and Sacramento County, a detailed analysis of the prepositioning of strategic resources before the disaster (and its effect on the disaster's aftermath) has not been performed. That phase of the plan is important because the efficiency of subsequent logistics (such as the distribution of supplies to affected areas during the disaster) highly depends on those strategic decisions. Help from FEMA in identifying candidate relief locations is a first step in that analysis. However, establishing each location's level of contribution and understanding how they would interact with affected areas in a disaster is a complicated question, which is better addressed via mathematical optimization and/or simulation models.

C. LITERATURE REVIEW

"ARkStorm" (Atmospheric River 1000 Storm) is a hypothetical flooding scenario created by USGS with 19 U.S. partners (USGS, 2011). ARkStorm studies the impact of a major catastrophic flood of similar size to the above mentioned 1862 flood. The major focus of the study is the economic effect of the flooding. The lost revenue from destroyed produce and killed livestock impart a heavy financial impact on the state, totaling an estimated $1 trillion. Ocean wave heights, possible landslides and their effects on transportation and repair are discussed, and recommendations about policy changes are given.

Nissen (2011) uses contingency theory to model the 2004 Indian Ocean disaster, in which an earthquake and tsunami killed over 230,000 people in 14 countries. He analyzes the international response and finds that many of their operations are dynamic, so they cannot be captured by a static model that does not account for time. He simulates six months of relief effort by government and nongovernment organizations in several time steps, and compares his simulated results to actual relief effort data. He finds that dynamic models are more reliable when modeling large international responses to disasters.

Renne, Sanchez, and Litman (2008) study the 2005 hurricanes Katrina and Rita. They evaluate how people without vehicles, elderly, disabled, and low-income families respond to the disasters. They use a multimodal approach to model an integrated evacuation system that addresses these individuals. Their research stresses the importance of coordination between government and nongovernmental organizations. The study recommends policy changes at every level of disaster planning to address these individuals' needs.

Heidtke (2007) studies the problem of prepositioning and delivering critical commodities following a disaster. He uses the response to hurricane Katrina to find practices that need improvement. He discusses strategies that help ensure commodities are available at the right time and location: prepositioning, preemptive federal action, time-phased deployment, and surge transportation. His approach employs an earlier version of the optimization model used in this thesis, and applies it to a hurricane scenario and a nuclear explosion scenario in the Washington, D.C., metropolitan area. He shows that stochastic optimization can be a useful strategic tool to help decision-makers plan for a given type of disaster under uncertainty in its severity.

Mitsotakis and Kassaras (2010) use linear programming to optimize the response to an earthquake on a Greek island. This is a special type of disaster relief because of the topography of the island and the fact that all resources can arrive only by aircraft or ship.

Salmeron and Apte (2010) further study the use of stochastic optimization for strategic prepositioning of resources in a natural disaster. They use a two-stage prepositioning optimization model (POM) to determine the decisions that have to be made prior to and after a disaster. They include factors such as vehicles used to rescue people or deliver supplies, casualties, population needing mass housing, and expansion possibilities, as limited by the available budget. The study determines the optimal prepositioning of resources given probabilities for multiple possible disaster scenarios. This thesis uses the POM and applies it to modeling flooding scenarios in the Sacramento region.

D. THESIS ORGANIZATION

The remainder of this document explores the use of the POM in selected scenarios associated with flooding in the Sacramento region, and discusses the results obtained.

Chapter II introduces different approaches to plan and model flood disasters. It introduces the POM, and discusses how it can be used to guide in the planning of future floods in the Sacramento region. The selection process for the relief locations (RLs), vehicles used and affected areas (AAs) is described at length. The different populations involved in a flood disaster are designated. The data gathered for this thesis and its input into the model are explained. This includes the scenario selection and other assumptions made to complete the input data. Chapter III explains the results of the POM for the selected scenarios. Chapter IV summarizes our findings and describes future work to help planning for other disasters.

Two appendices include a detailed description of the mathematical formulation and detailed travel time data used in our test cases, respectively.

II. OPTIMIZATION MODEL AND TEST CASE DESCRIPTION

A. MODELING FLOOD DISASTERS

A disaster can happen at many different locations, levels of severity, and according to other unpredictable factors, which makes the planning problem complicated. As a result, there are multiple approaches to disaster planning.

For example, planners may consider a worst-case disaster like ARkStorm (USGS, 2011). This scenario posits the catastrophic flood in the Sacramento region described in Chapter I. C. Planning against this pessimistic scenario also protects against many other, less severe situations in which the flooding could happen. However, planners may deem that the required preparation against such an unlikely event is too conservative and economically unacceptable.

Planners may also evaluate all the foreseen disaster scenarios and plan for an average scenario. For example, if a county could have between 50,000 to 100,000 people in need of evacuation, the plan could be devised for evacuating 75,000 people. This is an attractive approach for disaster planners. For example, FEMA uses the average approach when planning for disaster relief funds to individuals for future disasters (FEMA, 2008). FEMA is now trying to improve the average approach by adding demographics and specific location data to better average the costs of expected disasters. The disadvantage of this approach is that the planning for an average situation is not necessarily representative of and/or effective against each individual scenario.

Planning for the most likely scenario is also an attractive approach for planners, because it allows them to focus on a specific situation. However, the disaster relief established for that scenario, again, may not be suitable to cope with another scenario. In particular, the omission of less likely, more catastrophic scenarios is a key shortcoming of this approach.

Since disasters are inherently uncertain, a stochastic model that considers all foreseen events simultaneously can improve the planning against those events.

B. PREPOSITIONING OPTIMIZATION MODEL

The POM is a multi-objective, two-stage, stochastic, mixed-integer program. It recommends the best RLs to preposition supplies prior to disaster in order to help potential AAs under a number of disaster scenarios (Salmeron & Apte, 2010).

The AAs are locations that could be affected by a disaster. The population in these AAs are people that do not successfully evacuate prior to the disaster, and we separate them into three categories dependent on their needs. The first category is the emergency population (EP), who are the injured and/or in need of emergency evacuation to a facility that can administer medical assistance. The second category of population is the affected population (AP), who can stay in the AA, but need resources to be delivered in order to survive. The last population is the displaced population (DP), who will need to be transported to a RL for emergency shelter. Each AA has a certain number of each of these three populations in any given scenario. AAs can receive supplies via land or air, depending on their characteristics.

Inputs to the POM that are constant:

- The EP, AP, and DP populations for a given scenario
- Baseline travel times between each RL to each AA for each vehicle
- Availability of airports to support fixed wing and helicopters for each AA
- Data on vehicles available, air capability, medical capability, mass housing capability, and storage capacity for each RL
- Data on DP transport capability, commodity carrying capability, EP transport capabilities, and availability for each vehicle
- Expansion costs and availability for warehouse, medical, vehicle, and mass housing expansions

Resources such as warehouses, medical facilities, and shelter can be prepositioned at RLs in preparation for (and long before) a disaster. A RL has an assumed initial capacity of each of the above resources, for example, space that can be used for storage of commodities, and mass housing for the DP. If the RL is medically capable, then it has a limited number of the EP that it can treat. Each RL also has a specific air capability.

Vehicles (air and land) must be available and in place to rescue the EP and transport them to a medically-capable RL, transport the DP to a RL with mass housing capability, and transport commodities from a RL to the AP. Each vehicle has its own capability defined in terms of speed, range, availability, cargo carrying capacity, emergency rescuing capabilities, and personnel transport capabilities. Air vehicles are distinguished from land vehicles in that they may only take off from and land in RLs and AAs that have the capability.

Parameters that can be changed in successive runs of this model are:

- Budget levels available for use in expansions ($)
- EP survivor levels (the percentage of EP that survive once transported)

The POM is multi-objective because the overall goal is minimizing the casualties resulting from failing to meet the demands of the three populations, while maximizing the number of DP moved to RLs. The two-stage, stochastic nature of POM comes from the strategic decisions that need to be made under uncertainty, i.e., before the actual scenario is realized. First-stage variables include expansion for health-care facilities, warehouses and mass housing shelters at the RLs, and expansion for ramp space at the AAs. The second stage of the model includes decisions made during the 72 hours after the disaster, including additional vehicles needed, EP rescue and transportation to medical facilities at RLs, transportation and delivery of commodities to AAs, and transportation of DP to RLs. The POM is a mixed-integer program because some of the decision variables such as number of point-to-point trips made and additional vehicles used must be integer.

Outputs to the POM:

- Optimal expansions of warehouses, medical facilities, vehicles, and mass housing locations
- Casualties (persons)
- Supplies used (ft^3 x 1000)
- Vehicles used
- Populations (persons) and Supplies transported (ft^3 x 1000)

For completeness, the formulation of the POM (Salmeron & Apte, 2010) appears in Appendix A.

C. SACRAMENTO REGION DATA

1. Data for Affected Areas

We select eight AAs as shown in Figure 1, to encompass population in the Sacramento and Yolo counties that would be affected by a large flood in the Sacramento region. Each of these areas has an airport or large staging area where commodities can be offloaded. Table 1 describes the AAs and lists those possible offloading locations. AA1 through AA6 are in Sacramento County, and AA7 and AA8 are in Yolo County.

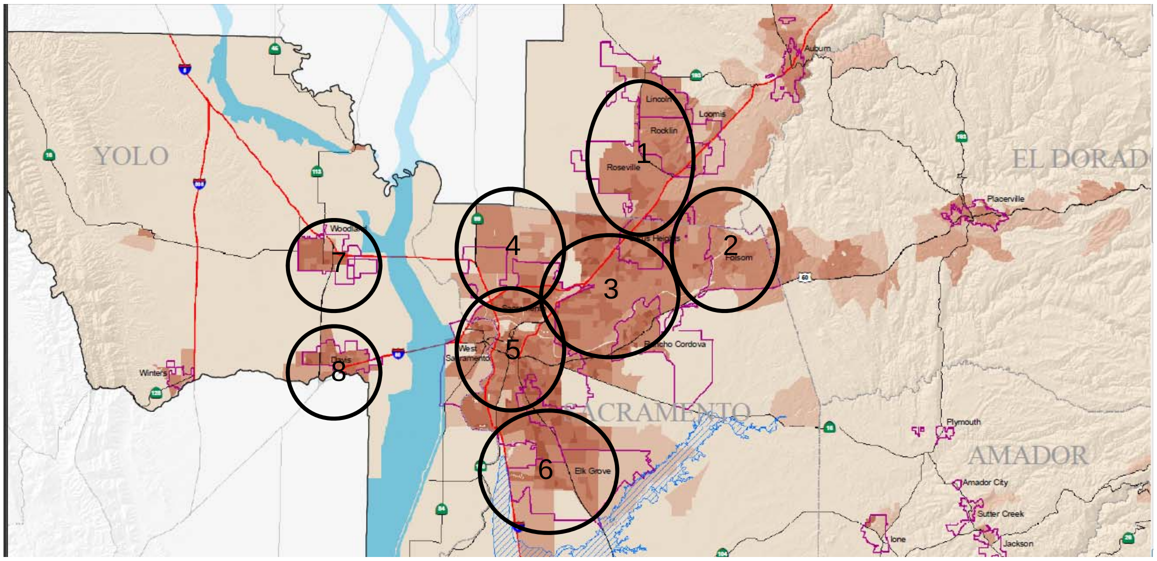


Figure 1. Geographical locations of the eight AAs selected for our study

Affected area	Description	AA offload location
AA1	Roseville, Rocklin, and Lincoln urban areas	Lincoln airport
AA3	Urban Rancho Cordova	California Exposition Center
AA4	Urban Sacramento Center	Sacramento international airport
AA5	Urban West Sacramento	Sacramento executive airport
AA6	Urban Elk Grove	Borges Clarksburg airport and CHP academy airport
AA7	Suburban Woodland	Woodland airport
AA8	Suburban Davis	Davis airport

Table 1. Locations for offloading in each AA

The selected locations in each AA have space available to offload goods. AA2 and AA3 do not have airports, so we assume a mall parking lot and California Exposition Center (CALEXPO) as suitable substitutes. The airports have a specific amount of ramp space that could be used for incoming aircraft offload. This is important to quantify so aircraft do not bring in more commodities than an airport can offload. Because in this thesis it is postulated that all shipping containers carried by vehicles are over 5 feet tall, we conservatively assume that the ramp space is covered by 5-foot-tall containers. In this manner, the raw square footage of the ramp space can be converted into cubic feet capacity to match that of vehicles and warehouses.

Table 2 gives the information gathered for the ramp space in each AA. For AA1, the Lincoln Airport is suitable to offload commodities (Airport Navigation (AIRNAV) Lincoln, 2011). In AA2 and AA3 there are no airports or room for expansion, so no fixed-wing aircraft can land there, but CALEXPO (2011) can be used for helicopters.

Sacramento International Airport at AA4 has large ramp areas that could be used in a disaster (AIRNAV Sacramento, 2011). Sacramento Executive airport is also a large airport that can be used for AA5 (AIRNAV Sacramento Executive, 2011). In AA6, two airports have sufficient ramp space (AIRNAV Borges Clarksburg 2011, AIRNAV CHP, 2011). These airports are farther away from downtown Sacramento so their ramp space expansion costs are assumed lower. The same is true for AA7 and AA8 in Yolo County. AA7 has ramp space available at Woodland Airport (AIRNAV Woodland, 2011), and AA8 has the Davis Airport (AIRNAV Davis, 2011).

Affected area	**Initial capacity (ft^3 x 1000)**	**Max. expansion (ft^3 x 1000)**	**Expansion costs (\$/ ft^3 x 1000)**
AA1	3,000	400	30,000
AA2	0	0	0
AA3	0	0	0
AA4	12,900	400	30,000
AA5	8,659	1,000	30,000
AA6	1,017	200	20,000
AA7	1,011	500	20,000
AA8	794	500	20,000

Table 2. Ramp space at AAs

The population for each AA (see Table 3) is from City-data (2010). Population is used later in this thesis to set up different scenarios of affected EP, AP, and DP as fractions of the total population. Each fraction will represent an estimate of elderly population and people in the AA without a vehicle (FEMA, 2006).

Afected area	Population
AA1	213,468
AA2	51,884
AA3	160,561
AA4	113,368
AA5	138,692
AA6	266,187
AA7	53,690
AA8	64,938

Table 3. Population in each AA

2. Data for Relief Locations

FEMA has studied the flooding problem in Sacramento, and has proposed multiple locations that could be used for disaster relief (FEMA, 2006). A subset of these locations (Figure 2 and Table 4) constitute the RLs in our study.

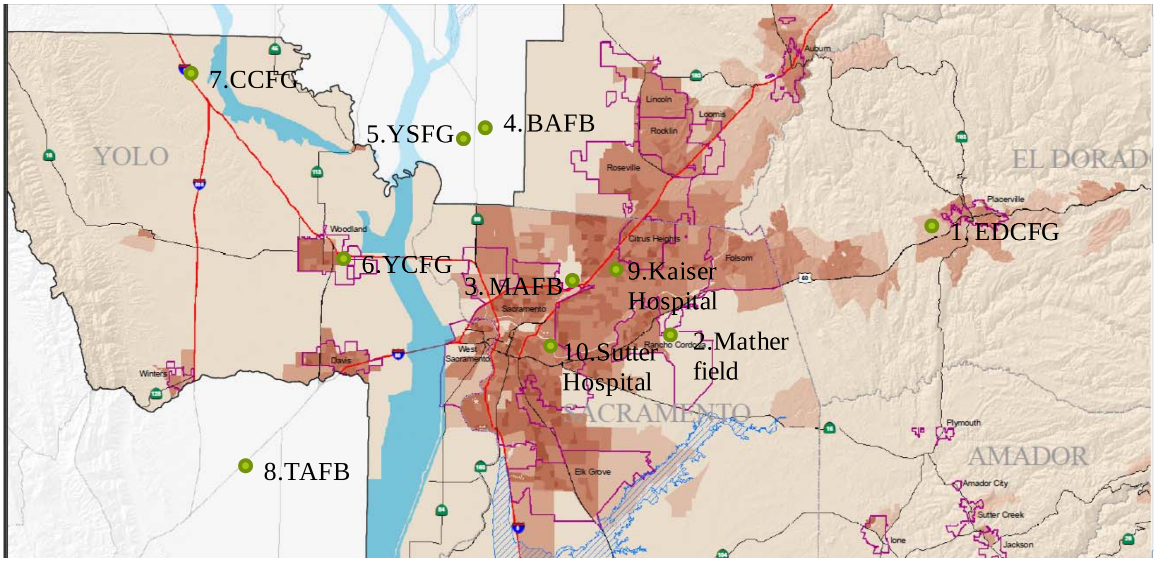


Figure 2. Geographical locations of the 10 RLs selected for our study

Relief location	Name	Description
RL1	El Dorado CFG	Small county fairgrounds
RL2	Mather Field	Decommissioned Air Force base (AFB)
RL3	McClellan Air Park	Decommissioned AFB
RL4	Beale AFB	Large active AFB
RL5	Yuba/Sutter CFG	Medium-sized county fairgrounds
RL6	Yolo CFG	Large county fairgrounds
RL7	Colusa CFG	Medium-sized county fairgrounds
RL8	Travis AFB	Large active AFB
RL9	Kaiser Hospital	Large hospital
RL10	Sutter Hospital	Large hospital

Table 4. RL names and descriptions

Warehouse capacity determines the amounts of commodities that can be prepositioned at RLs prior to a disaster. RL1–RL8 have warehouses in place (FEMA, 2006), all of which can be further expanded as shown in Table 5. RL9 and RL10 do not have initial capacity available. We assume warehouses are filled with 10-foot storage containers.

Relief location	Initial capacity (ft^3 x 1000)	Max. expansion (ft^3 x 1000)	Expansion cost ($\$/ft^3$ x 1000)
RL1	242	300	200,000
RL2	450	600	100,000
RL3	600	800	100,000
RL4	550	700	100,000
RL5	694	800	100,000
RL6	464	500	200,000
RL7	512	550	200,000
RL8	500	550	200,000
RL9	0	150	300,000
RL10	0	150	300,000

Table 5. Warehouse capacity and expansion costs

The actual warehouse storage capacity at RL2, RL3, RL4, and RL8 is more than indicated, but because these are active military bases or airfields, only a fraction of their warehouse space is assumed to be available for storage of commodities. RL9 and RL10 are hospital locations and have limited amount of space to expand as storage.

Each RL also has the ability to house mass amounts of people. FEMA (2006) has assessed the parking and hard surface area at these RLs and has determined possible mass housing locations. For this thesis it is assumed 20% of the parking and hard surfaces at these RLs can be used for mass housing and shelter. Using an estimate of 40 square feet of shelter space needed per person (Red Cross, 2002), the DP initial capacities and potential expansion for each RL is indicated in Table 6.

Relief location	Initial capacity (persons)	Max. expansion (persons)	Expansion cost ($/person)
RL1	654	500	1,200
RL2	5,000	2,000	1,200
RL3	5,000	2,000	1,200
RL4	5,000	2,000	1,200
RL5	3,049	1,000	1,200
RL6	11,979	2,000	1,200
RL7	2,178	1,000	1,200
RL8	5,000	2,000	1,200
RL9	0	500	1,200
RL10	0	500	1,200

Table 6. Shelter capacity and expansion costs

Each RL also has a capacity to house health-care personnel in support of EP, as shown in Table 7. Health-care personnel are doctors and nurses that can assist the EP. RL9 (Kaiser Hospital) and RL10 (Sutter Hospital) are large hospitals that can serve as EP focal points in a disaster (Kaiser, 2010; Sutter, 2010).

Relief location	Initial capacity (health care personnel)	Max. Expansion (health care personnel)	Expansion costs ($/health care personnel)
RL1	0	0	0
RL2	150	50	2,000
RL3	150	50	2,000
RL4	200	50	2,000
RL5	0	0	0
RL6	0	0	0
RL7	0	0	0
RL8	250	100	1,500
RL9	500	200	1,500
RL10	600	200	1,500

Table 7. Health-care facility capacity and expansion costs

California also has three "mobile field hospitals" (MFH) that can be set up at RLs, provided the RL is sufficiently large. The MFHs can be sent to predesignated locations and set up in preparation for a disaster (California Department of Public Health (CDPH), 2010). There are four RLs that could handle a MFH. Since RL8 (Travis AFB) is farther away from Sacramento, we select RL2 (Mather Field), RL3 (McClellan Air Park), and RL4 (Beale AFB). Through private communications with CDPH's David LeMay and information by Heller (2007), we estimate approximately 150 medical personnel per MFH, as indicated in Table 7. Another 50 medical personnel can be expected from RL4 (Beale AFB) because of their base medical staff and clinic that would also be used in a disaster (Beale, 2011). RL8 (Travis AFB) has a large hospital and could also assist in a local disaster (Travis, 2011).

This thesis assumes each medical personnel can treat an average of 10 people over the 72-hour postdisaster period. For example, from Table 7, we assume that RL2 has initially 150 medical personnel available to treat up to 1,500 EP, and that up to 50 more can be prepositioned (i.e., available on call) at a cost of $2,000 per health-care provider.

3. Data for Vehicles

In order to rescue the EP, deliver commodities to the AP, and transport the DP, vehicles are needed. This research considers the many different modes of transportation from multiple agencies that can be used to serve the three needy populations. Our test case assumes the transportation assets and data shown in Tables 8 and 9. All these data have been compiled during multiple interviews, electronic communications, and fact sheets provided by different agencies, as described below.

In 2010, 31.5 million passengers rode on public transportation in the Sacramento region. In a disaster, local buses and shuttles would be very useful in transporting displaced people from AAs to RL shelters. The bus and shuttle information has been acquired from Sacramento Regional Transit (2010).

Information on the UH-1H helicopter was provided by CALFIRE (2009). The primary use of the UH-1H would be in rescuing of the EP.

Vehicle type	Availability (# of units)	Max. expansion (# of units)	Expansion cost ($ / ft^3 x 1000)
BUS	235	30	8,000
SHUTTLE	17	10	10,000
UH1H	9	4	1,500,000
VAN48	30	5	27,970
VAN28	8	5	22,000
TRUCK18	2	2	15,000
AST	25	5	500,000
C130	24	12	70,314
C17	5	2	175,000
HMMWV	10	10	40,000
HC130	5	4	75,000

Table 8. Vehicle capacity and expansion costs

Vehicle type	Commodities capacity (ft^3 x 1000)	Survivors capacity (persons)	Worker capacity (persons)	Displaced capacity (persons)	Availability (hours)	Operating range (hours)
BUS	0.6	0	5	48	68	12
SHUTTLE	0.4	0	40	40	65	12
UH1H	0.0	5	0	0	62	4
VAN48	5.5	0	3	40	65	17
VAN28	1.5	0	3	40	65	12
TRUCK18	1.0	0	0	0	68	10
AST	0.0	4	0	0	62	8
C130	4.5	0	92	92	60	5
C17	8.7	0	102	102	60	5
HMMWV	0.0	3	0	0	62	6
HC130	0.0	4	0	0	62	5

Table 9. Vehicle characteristics

California Department of Corrections and Rehabilitation (CDCR) owns vehicles that are used to transport commodities from prison to prison, which could be used in disaster relief. CDCR has provided the information for 48-foot vans, 28-foot vans, and 18-foot trucks. Vans can be used to transport commodities to the AP and also transport DP back to RLs, but trucks can only transport commodities to the AP.

CDPH (2010) has “ambulance strike teams” (ASTs) that are available during disasters for assisting in the rescuing of EP.

The National Guard has many assets that could be used during a disaster, especially C17s, C130s, and HMVEEs. Since these assets are in constant flux, we assume 24 C130s, 5 C17s, and 10 HMMWVs are initially available (Air Force, 2011, HMMWV, 2011)

We assume the Coast Guard also uses its available HC130 assets to assist in the rescue of the EP during a disaster. The information on the HC130 is found in their fact sheet (Coast Guard, 2011).

The vehicles have associated travel times from each RL to each AA. These times are a function of their speed and the distance covered. The initial travel times are located in Appendix B. For simplicity, we use a central location in each AA to calculate the distance and travel time between given RLs and AAs.

4. Scenario Data

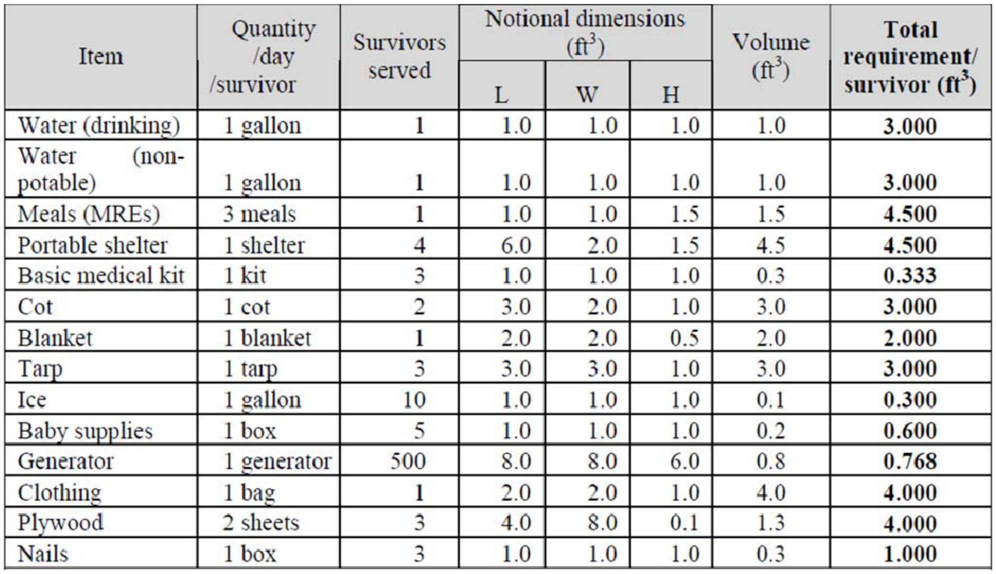
Flooding disasters can cause different damage depending on their location and severity. In this thesis we evaluate four possible scenarios with increasing severity and decreasing probability. Each scenario has different levels of assumed DP, EP, AP and commodities required. The EP, AP, and DP are a different percentage of the population of the AA, depending on the scenario. Most of the population in the AAs are expected to evacuate before the flood occurs due to flood warning of rising rivers and continued rain. The population that is left and need assistance is the focus of these scenarios.

The first scenario, “Scenario 1,” is a small flood with modest impact in the Sacramento region. Evacuations of most of the AAs happen prior to the flood.

		Affected population		
Afected area	**EP (persons)**	**(persons)**	**Commodities (ft^3 x 1000)**	**DP (persons)**
AA1	1,494	17,077	198	4,269
AA2	363	4,151	48	1,038
AA3	1,124	12,845	149	3,211
AA4	794	9,069	105	2,267
AA5	971	11,095	129	2,774
AA6	1,863	21,295	247	5,324
AA7	376	4,295	50	1,074
AA8	455	5,195	60	1,299
Total	7,440	85,023	986	21,256

Table 10. Scenario 1 demand for the different affected populations

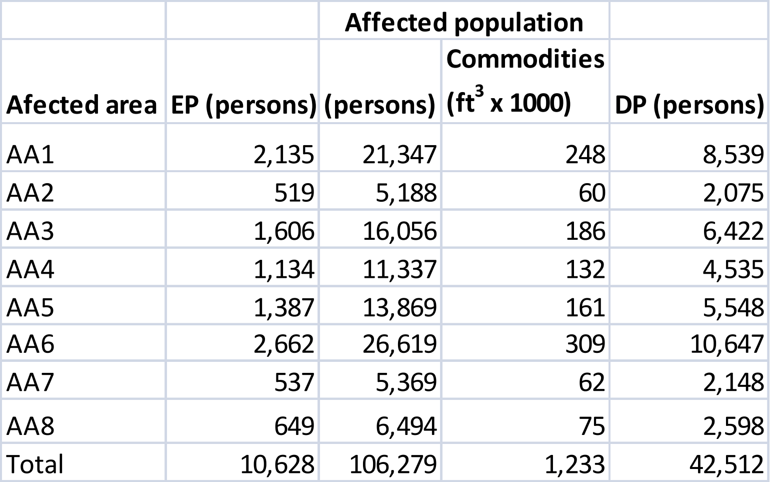
In Scenario 1, the AP is 8% across all AAs, which is associated with the 8% of Sacramento residents that do not have a vehicle (FEMA, 2006). Table 11 shows different commodities that might be needed during a disaster. For Scenario 1, water, food, generator, and basic medical kit are needed by the AP, which adds up to 11.6 ft^3 per person. Because the flood is isolated and minimal, the DP in this scenario is assumed to be 2% of the population, and the EP is assumed to be 0.7% of the population. The EP figure is estimated by combining the number of people that are injured in the flood, and the portion of the large percentage of elderly people that need emergency evacuation in the Sacramento region (FEMA, 2006). Details are given in Table 10. During the author's discussions with Cal EMA, officials agreed that this is a likely next-flood scenario, and that a 40% probability is a reasonable estimate.



Item	Quantity /day /survivor	Survivors served	Notional dimensions (ft^3)			Volume (ft^3)	**Total requirement/ survivor (ft^3)**
			L	W	H		
Water (drinking)	1 gallon	1	1.0	1.0	1.0	1.0	**3.000**
Water (non-potable)	1 gallon	1	1.0	1.0	1.0	1.0	**3.000**
Meals (MREs)	3 meals	1	1.0	1.0	1.5	1.5	**4.500**
Portable shelter	1 shelter	4	6.0	2.0	1.5	4.5	**4.500**
Basic medical kit	1 kit	3	1.0	1.0	1.0	0.3	**0.333**
Cot	1 cot	2	3.0	2.0	1.0	3.0	**3.000**
Blanket	1 blanket	1	2.0	2.0	0.5	2.0	**2.000**
Tarp	1 tarp	3	3.0	3.0	1.0	3.0	**3.000**
Ice	1 gallon	10	1.0	1.0	1.0	0.1	**0.300**
Baby supplies	1 box	5	1.0	1.0	1.0	0.2	**0.600**
Generator	1 generator	500	8.0	8.0	6.0	0.8	**0.768**
Clothing	1 bag	1	2.0	2.0	1.0	4.0	**4.000**
Plywood	2 sheets	3	4.0	8.0	0.1	1.3	**4.000**
Nails	1 box	3	1.0	1.0	1.0	0.3	**1.000**

Table 11. Possible commodities needed during a disaster (From Heidtke 2007)

We model "Scenario 2" as a more severe flood than Scenario 1. AA6 is flooded and fixed-wing aircraft cannot land in this area.



		Affected population		
Afected area	**EP (persons)**	**(persons)**	**Commodities (ft^3 x 1000)**	**DP (persons)**
AA1	2,135	21,347	248	8,539
AA2	519	5,188	60	2,075
AA3	1,606	16,056	186	6,422
AA4	1,134	11,337	132	4,535
AA5	1,387	13,869	161	5,548
AA6	2,662	26,619	309	10,647
AA7	537	5,369	62	2,148
AA8	649	6,494	75	2,598
Total	10,628	106,279	1,233	42,512

Table 12. Scenario 2 demand for the different affected populations

The AP in Scenario 2 is a combination of the 8% population without vehicles, and 2% of the rest of the population including elderly and people below the poverty line that do not have the financial means to leave (FEMA, 2006). The commodity demand for each person in the AP is assumed to remain at 11.6 ft^3 per person. Due to increased flooding, the DP is assumed to increase to 4% of the entire population of the AAs. The EP is 1% of the population due to increased flooding and disabled and elderly personnel that need medical attention while being moved. Details are given in Table 12. Cal EMA officials agree that this is another likely scenario, and that a 25% probability of this being the next flood event is a reasonable estimate.

For "Scenario 3" we assume the Sacramento River floods and the transit across it for land vehicles takes 50% longer then nominal time. In this scenario the model multiplies the travel time from the baseline travel time in Appendix B by 150% if the vehicle travels between a RL on one side of the river to an AA on the other side of the river. This slows down commodity deliveries, DP transportation, and transportation of EP across the river by all land vehicles.

		Affected population		
Afected area	**EP (persons)**	**(persons)**	**Commodities (ft^3 x 1000)**	**DP (persons)**
AA1	2,668	25,616	528	12,808
AA2	649	6,226	128	3,113
AA3	2,007	19,267	397	9,634
AA4	1,417	13,604	280	6,802
AA5	1,734	16,643	343	8,322
AA6	3,327	31,942	658	15,971
AA7	671	6,443	133	3,221
AA8	812	7,793	161	3,896
Total	13,285	127,535	2,627	63,767

Table 13. Scenario 3 demand for the different affected populations

In this scenario, the AP comprises of 8% of people without vehicles and 4% of elderly and people below the poverty line. Since the flood is more severe, the AP is assumed to need 20.6 ft^3 per person to include water, food, shelter, cot, blanket, and baby supplies. The flooding is more widespread, so the DP is 6%. The EP is assumed to be

1.25% of the population in this scenario who need immediate rescue and medical assistance, i.e., the disabled and elderly. Cal EMA officials agree that this is a possible flooding scenario, and estimate a 20% probability of it being the next flood event.

"Scenario 4" is a major flood. RL4 and RL5 are disconnected from all AAs and cannot be reached by land vehicles. Also, the Sacramento River is flooded and travel time across it by land vehicles takes 75% longer than normal. This increased time is applicable to land travel originating from RL1-RL5, RL9, and RL10 to AA7 and AA8, and from RL6-RL8 to AA1-AA6.

		Affected population		
Afected area	**EP (persons)**	**(persons)**	**Commodities (ft^3 x 1000)**	**DP (persons)**
AA1	3,202	29,886	616	17,077
AA2	778	7,264	150	4,151
AA3	2,408	22,479	463	12,845
AA4	1,701	15,872	327	9,069
AA5	2,080	19,417	400	11,095
AA6	3,993	37,266	768	21,295
AA7	805	7,517	155	4,295
AA8	974	9,091	187	5,195
Total	15,942	148,790	3,065	85,023

Table 14. Scenario 4 demand for the different affected populations

Many AAs are flooded in Scenario 4 causing the AP to increase to 14%. Commodities required by the AP remain 20.6 ft^3 per person as in Scenario 3. The DP is 8%, which matches Cal EMA's expectation on the amount of people for whom they will have to find housing in a major flood, also concurring with FEMA estimates (FEMA 2006). The EP for Scenario 4 increases to 1.5% due to the major flooding impact. Details are indicated in Table 14. Cal EMA officials agree that this is a possible flooding scenario, and that 15% probability is a reasonable estimate.

POM allows for a scenario-dependent number of workers to deliver commodities to the AP. These workers travel from the RLs to the AAs using the available vehicles, therefore sharing space with commodities (see Table 9). For simplicity, we assume that one worker is needed per 1,000 ft^3 of delivered commodities in all scenarios. Scenario totals are summarized in Table 15

				Affected population		
	Probability (%)	**Travel considerations**	**EP (persons)**	**(persons)**	**Commodities (ft^3 x 1000)**	**DP (persons)**
Scenario 1	40	None	7,440	85,023	986	21,256
Scenario 2	25	Airport at A6 disabled	10,628	106,279	1,233	42,512
Scenario 3	20	Travel across river delayed	13,285	127,535	2,627	63,767
Scenario 4	15	Travel across river delayed, RL4 and RL5 isolated	15,942	148,790	3,065	85,023

Table 15. Scenario summary

5. Other Data

As suggested by Cal EMA officials, we start with an initial budget of $0 to use in expansions and increase it up to $5,000,000 in $1,000,000 increments. We also test values of 60% and 90%, respectively, for the percentage of the EP that would survive if they are rescued. Finally, we assume the EP suffers 10 casualties per 1,000 ft^3 of undelivered commodities.

The POM allows for the relaxation of the first objective (casualties from the EP and AP) to further optimize the second objective (meeting the DP demand). Cal EMA officials maintain that the reduction in casualties is, to a large extent, the most important priority, and that there should be very little relaxation of the first objective for the benefit of the second. Accordingly, we set the relaxation rate at 1%.

We use the POM as implemented by Salmeron and Apte (2010) using the General Algebraic Modeling System (GAMS) (GAMS 2011) and using the GAMS/CPLEX solver. The runs are carried out on a Toshiba 2.0 GHz laptop computer with 4 GB of RAM. In each run the dimensions of the model is approximately 37,000 constraints and approximately 83,000 variables, of which 23,000 are integer variables. A typical run of any of the above cases takes approximately one minute with a 5% optimality gap. Typical solution time for optimality is usually within 30 minutes. All results in this thesis are solved with a 5% optimality gap.

III. RESULTS

A. OVERVIEW

In this thesis the EP survival rate and budget levels are varied to analyze how the budget is allocated to reduce the number of casualties, while maximize the transport of DP. Warehouse capacities at the RLs are also reduced to analyze how the budget will be allocated if the county fairgrounds and bases could only store commodities in part of their warehouse space due to reduced availability. These results show what vehicles are needed, and what expansions would optimally reduce the number of casualties, while maximizing transportation of EP.

B. CASE 1: 60% SURVIVAL RATE FOR EMERGENCY POPULATION

1. Overview

For this case, we set the survivor rate at a pessimistic 60%, that is, we assume that 40% of the rescued EP will perish (either before or at the medical facility where they are transported). Within this case we consider several budget levels ranging from no budget (i.e., only initial capacity can be used) to $5 million. Table 16 shows the results for each of these budget levels. With a budget of $0 there are 4,490 expected casualties, mostly due to the assumed 40% casualty rate. The EP casualties make up 4,475 of these casualties. The casualties to the AP are minimal at 15 people. This shows the RLs initial warehouse space and the vehicles used to transport commodities are enough, before expansion, to provide for the AP.

When $1 million budget is available, the POM indicates that an additional 125 EP persons and 15 AP persons can be saved with a minimal expansion in health care personnel and transportation (vehicles that can save EP, see Section III.B.2). However, higher budget levels cannot reduce the expected number of casualties below 4,350, which is approximately 40% of the total expected EP (and cannot survive even if they are rescued). Remark: A small difference of less than 100 survivors is due to our optimality gap of 5% when solving POM, as well as the 1% adjustment allowed to reduce the number of unmet demand for DP when solving for the second objective function. This also explains the apparent increase in casualties in the \$2 million to \$5 million excursions. (That is, if the allowed adjustment were set to 0%, total casualties would remain at 4,350, but the number of stranded DP would be slightly higher than shown in the table.) In the DP category, with \$0 budget, 13,875 people are not moved to mass housing because the initial capacity for mass housing at the RLs is too small to support them. Consequently, once the budget is increased, POM recommends shelter expansion.

We further analyze the use of additional budget and find that the model recommends allocating it to expand mass housing, until a budget level of \$16.2 million. At this point, the maximum capacity for expansion (based on available space) at RLs is reached, and even then 8,138 people of the DP are still stranded.

Consistently with the low number of AP casualties (and the fact that these are due to the above-mentioned 1% relaxation), neither warehouse capacity nor ramp space capacity are expanded at any budget level.

Budget (\$)	EP casualties (persons)	AP unmet commodities (ft^3 x 1000)	Total casualties (persons)	Stranded DP (persons)	Healthcare expansion cost (\$)	Warehouse expansion cost (\$)	Ramp expansion cost (\$)	Mass housing expansion cost (\$)	Transportation cost (\$)	Total cost (\$)
0	4,475	1	4,490	13,876	0	0	0	0	0	0
1,000,000	4,350	0	4,350	13,478	39,816	0	0	795,184	96,750	931,750
2,000,000	4,364	3	4,394	12,978	39,816	0	0	1,795,184	96,750	1,931,750
3,000,000	4,364	3	4,394	12,478	39,816	0	0	2,795,184	96,750	2,931,750
4,000,000	4,370	2	4,394	11,978	39,816	0	0	3,795,184	96,750	3,931,750
5,000,000	4,370	2	4,394	11,478	39,816	0	0	4,795,184	96,750	4,931,750

Table 16. Objective function and budget allocation with EP survivor rate at 60%

2. Detailed Results for \$1 Million Budget Excursion

We now describe select, detailed results of the POM for the \$1 million budget excursion. Table 17 shows the details of the recommended expansion in transportation vehicles. Depending on the scenario, the only additional vehicles needed are one AST, one HC130, and/or one HMMWV, all of which transport EP.

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
AST	0	1	1	1
HMMWV	0	1	1	0
HC130	1	1	0	0

Table 17. Transportation expansion details for each scenario under an assumed $1 million budget

In Table 18, we display the movement by AST of EP from the AAs to the RLs if Scenario 1 occurs. The ASTs rescue the EP from AA3, AA5, and AA6 and transport them to RL3, RL9, and RL10. The ASTs are transporting people mainly to the major hospitals RL9 and RL10. The rest of the AST trips are taking EP to one of the MFHs at RL3. The ASTs make many small trips from AAs to medical facilities in the 72-hour period. In Scenario 1, all the EP from AA3 and AA5 (see also Table 10) is entirely transported by AST. For all other AAs, other emergency rescue vehicles are utilized.

From	**To**	**EP moved (persons)**	**# trips**
AA3 (Cordova)	RL3 (McClellan)	1124	281
AA5 (Sacramento)	RL9 (Kaiser)	971	243
AA6 (Elk Grove)	RL10 (Sutter)	1016	254

Table 18. AST movement of EP in Scenario 1

In Table 19, we show the commodities delivered from each RL to each AA by the VAN48 vehicle. This vehicle is primarily being deployed with commodities out of RL6-RL8, and it supplies all areas but AA8.

From	To	Commodities delivered (ft^3 x1000)	# trips
RL1 (Dorado)	AA2 (Folsom)	49	42
RL6 (Yolo)	AA1 (Roseville)	198	62
RL6 (Yolo)	AA5 Sacramento)	32	15
RL7 (Colusa)	AA6 (Elk Grove)	247	62
RL7 (Colusa)	AA7 (Woodland)	50	81
RL8 (Travis)	AA3 (Cordova)	149	69
RL8 (Travis)	AA4 (Center)	106	55

Table 19. Commodities carried in the 48-foot vans in Scenario 1

Table 20 shows the bus trips to move the DP from the AAs to the RLs. Some of the trips are filled with people, but others still have capacity when they make certain trips. This is because the bus might have delivered some commodities to an AA, and is going to pick up more commodities from a RL that already has its mass housing area full.

The above are some detailed examples of results provided by POM. For conciseness, we do not show results for other resource types and/or scenarios.

From	To	DP moved (persons)	# trips
AA1 (Roseville)	RL8 (Travis)	2624	105
AA3 (Cordova)	RL3 (McClellan)	411	67
AA7 (Woodland)	RL1 (Dorado)	1074	38
AA8 (Davis)	RL7 (Colusa)	1299	105

Table 20. DP transportation by the Buses in Scenario 1

3. Analysis of the Stochastic Prepositioning Optimization Model Solution

Using the same excursion as in the above section, we evaluate the stochastic POM by comparing it with the deterministic POM's solution to the case where it has perfect knowledge about which scenario will occur (denoted here as "perfect knowledge"), and by calculating the value of the stochastic solution (Birge and Louveaux, 1997, pp. 137–152). Table 21 shows all the results.

Although the POM is bi-objective, we carry out the comparison for the first objective only, i.e., for total EP and AP casualties, and prior to solving the second objective (so the former is not affected by the potential 1% relaxation). The objective function value for the stochastic solution in this case is 4,307 casualties.

The perfect knowledge solution plans for each of the disaster scenarios individually considered. This produces a lower bound on the amount of casualties there could be. Of course, the perfect knowledge solution is not implementable because we cannot anticipate the actual disaster scenario.

In this excursion the perfect knowledge solution has an average of 4,283 casualties. Thus, the expected value of perfect information (i.e., the stochastic solution minus the perfect knowledge average) is 24 casualties. This shows the stochastic solution is also very close to the best-possible solution for each individual scenario, that is, it accommodates all scenarios simultaneously without being detrimental to any of them.

To calculate the value of the stochastic solution, we create a plan for the average scenario. In this scenario, the EP, AP and DP in each AA are calculated as a weighted average of those populations by scenario, as given in Tables 10, 12, 13 and 14, respectively. For example, the average EP in AA1 would be 2,145 people. Then, we calculate the optimal solution for this average scenario and test it against each original scenario individually considered. (To do this, we fix the first-stage decisions and solve for the second stage in each scenario.) The stochastic solution notably improves the solution that plans for an average scenario. In particular, Scenario 4 shows the largest deviation between the stochastic solution and the average planning solution. This shows that, when planning for an average scenario, the more catastrophic, less probable scenarios may not be properly represented. The value of the stochastic solution (i.e., the average scenario planning casualties minus those from the stochastic solution) is 443 fewer casualties. This shows that planning for the average case is inferior to the type of stochastic planning in the POM.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	average
planning with perfect knowledge (best case)	2,981	4,279	5,320	6,379	4,283
Planning for the average scenario	3,789	4,296	5,341	7,279	4,750
stochastic planning (via POM)	2,981	4,368	5,330	6,379	4,307

Table 21. Objective function (total EP and AP casualties) by planning approach

C. CASE 2: 90% SURVIVAL RATE

1. Overview

For this case, we set the survivor rate at an optimistic 90%. We again test several excursions from no budget to $5 million. Table 22 shows the results for these budget levels. With a budget of $0 there are 1,233 expected casualties. Like in Case 1, these are mostly due to the 90% survivor rate.

More than 150 additional people in the EP can be saved by spending part of the available budget in health-care providers and emergency transportation vehicles. AP casualties are minimal, which allows the budget to be allocated to other needs. Like in Case 1, there is no warehouse expansion, because the initial capacity suffices to meet the AP demand for commodities. This allows the remaining expansions to be allocated to mass housing.

At the $1 million budget level, slightly less is spent on mass housing expansion than in the previous case due to the increased expansion of transportation.

Budget ($)	EP casualties (persons)	AP unmet commodities (ft^3 x 1000)	Total casualties (persons)	Stranded DP (persons)	Healthcare expansion cost ($)	Warehouse expansion cost ($)	Ramp expansion cost ($)	Mass housing expansion cost ($)	Transportation cost ($)	Total cost ($)
0	1,233	0	1,234	13,884	0	0	0	0	0	0
1,000,000	1,079	0	1,079	13,491	28,974	0	0	771,026	181,000	981,000
2,000,000	1,080	0	1,080	12,991	30,163	0	0	1,769,837	175,000	1,975,000
3,000,000	1,080	0	1,080	12,501	30,163	0	0	2,749,837	200,500	2,980,500
4,000,000	1,080	0	1,080	11,991	30,655	0	0	3,769,345	193,000	3,993,000
5,000,000	1,079	0	1,079	11,491	30,655	0	0	4,769,345	191,000	4,991,000

Table 22. Objective function and budget allocation with EP survivor rate at 90%

2. Detailed Results for $1 Million Budget Excursion

If there is a $1 million budget available for expansion, the POM recommends that RL7 (Colusa) mass shelter is expanded to help shelter the DP in the surrounding area. Colusa is selected because of its initial low mass housing capacity and initial high warehouse capacity. The vehicles that are used for both delivering commodities and carrying DP take advantage of dropping off DP at a RL with mass housing available before picking up commodities. This serves both objectives better. Also, health-care providers are added to the MFH at RL3 (McClellan) to save the rest of the EP. McClellan is selected because of its minimal distance to the population centers.

	RL1	RL2	RL3	RL4	RL5	RL6	RL7	RL8	RL9	RL10
Warehouses (ft^3 x 1000)	0	0	0	0	0	0	0	0	0	0
Health care (Health care provider)	0	0	15	0	0	0	0	0	0	0
Shelter (persons)	0	0	0	0	0	0	643	0	0	0

Table 23. Expansion recommendations for Case 2 under an assumed $1 million budget

More money is spent for transportation in this case than in the same excursion in Case 1. In these scenarios additional AST are used in every scenario in order to assist in the transportation of the EP. Additional HMMWVs are used in Scenario 2, but unlike Case 1, no scenario requires the use of HC130.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
AST	3	2	4	4
HMMWV	0	2	0	0

Table 24. Vehicle expansion recommendations for Case 2 under an assumed $1 million budget

D. CASE 3: 90% SURVIVAL RATE WITH REDUCED INITAL WARHOUSE CAPACITY

1. Overview

This case seeks insight into where the model would allocate the budget if less warehouse space were available. Specifically, we pessimistically assume that only one quarter of the warehouse space described in Table 5 is available at each RL. (Actual warehouse availability is dependent, for example, on what events are happening at the AFB or county fairground.)

The AP casualties increase because of the large amount of unmet commodities. As expected, the majority of the budget is allocated to warehouse expansion. As the budget increases, the expanding warehouses continue in order to meet the AP needs. Details are given in Table 25.

The recommended investment on mass housing expansion decreases with respect to that in the previous two cases. In fact, it remains constant as the budget increases, until the warehouses are expanded to fully supply the AP.

Recommended health-care personnel expansion is also minimal, but of little concern given that the EP casualties are still at a minimum (except when there is no budget available), and due exclusively to the 90% survivor rate.

Budget ($)	EP casualties (persons)	AP unmet commodities (ft^3 x 1000)	Total casualties (persons)	Stranded DP (persons)	Healthcare expansion cost ($)	Warehouse expansion cost ($)	Ramp expansion cost ($)	Mass housing expansion cost ($)	Transportation cost ($)	Total cost ($)
0	1,226	718	8,407	13,876	0	0	0	0	0	0
1,000,000	1,070	714	8,208	13,844	0	695,000	0	65,000	232,043	992,042
2,000,000	1,069	708	8,154	13,795	1,400	1,597,450	0	161,150	222,500	1,982,500
3,000,000	1,069	702	8,094	13,795	1,400	2,597,450	0	161,150	222,500	2,982,500
4,000,000	1,069	696	8,034	13,795	1,400	3,597,450	0	161,150	222,500	3,982,500
5,000,000	1,069	690	7,974	13,795	1,400	4,597,450	0	161,150	222,500	4,982,500

Table 25. Objective function and budget allocation with EP survivor rate at 90% and one quarter initial warehouse space available

2. Detailed Results for $1 Million Budget Excursion

Assuming a $1 million budget, expansion details are provided in Table 26. Warehouses are expanded only at RL2 (McClellan) to supply the AP because of its lower warehouse expansion costs and its use as a major mass housing location. Health-care provider expansions are negligible. This shows the main reason for the reduction in EP casualties at the $1 million budget level is the expansion of EP transporting vehicles. Mass housing is expanded only at RL6 (Yolo).

	RL1	**RL2**	**RL3**	**RL4**	**RL5**	**RL6**	**RL7**	**RL8**	**RL9**	**RL10**
Warehouses (ft^3 x 1000)	0	7	0	0	0	0	0	0	0	0
Health care (Health care providers)	0	0	0	0	0	0	0	0	0	0.25
Shelter (persons)	0	0	0	0	0	54	0	0	0	0

Table 26. Expansion results for Case 3 under an assumed $1 million budget

The increase in transportation expansion is reflected on the additional vehicles utilized in all scenarios (see Table 27). The 48-foot van and 28-foot van are expanded because of their dual use as commodity carriers for the AP, and DP transporters. The AST's, HMMWVs, and HC-130 are also expanded to help rescue the EP.

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
VAN48	0	1	0	0
VAN28	1	0	0	0
TRUCK18	1	0	1	0
AST	0	1	0	4
HMMWV	5	2	5	1
HC130	0	1	0	0

Table 27. Vehicle expansion recommendations under Case 3 for an assumed $1 million budget

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IV. CONCLUSION AND RECOMMENDATIONS

This thesis has tested the use of the POM in a flooding disaster in the Sacramento region. We have considered a number of potential flooding scenarios and allow the POM to produce optimal prepositioning solutions at different budget levels. The results may be useful to guide FEMA's planners. For example they show that:

- The RLs that FEMA has already selected have enough warehouse space to support the AP in any of the flooding scenarios hypothesized in this thesis.
- The existing warehouse capacity should be monitored so it is not being used for other purposes prior to disasters. If the warehouses cannot hold the commodities needed to supply the AP then the casualties could increase significantly. Expansion at other locations (McClellan Air Park) is recommended.
- With existing resources, minor investment in additional health-care providers and emergency rescue vehicles, the EP can be moved to medical facilities. The assumed survival rate during transportation and/or at the medical facilities determines the actual number of survivors from this population.
- The designated RLs do not have adequate space to fully house the DPs in the scenarios envisioned in this thesis. Expansion at the Colusa County fairgrounds RL is recommended first. However, even when the assumed maximum expansions are carried out, space available remains insufficient. Thus, hotels in surrounding cities not affected by the flood and additional RLs are needed. These must be designated and included at the planning level.
- The ramp space designated at the AAs that have airports is sufficient to offload the commodities delivered by aircraft, and does not need to be expanded.

- Depending on the scenario, a modest number of additional transportation vehicles are recommended. These include: one to four ASTs, one to five HMMWVs and one HC130 for transporting EP; and, one VAN48, one VAN28 and one TRUCK18 for transportation of DP and delivery of commodities to the AAs. These additional vehicles reduce the number of casualties, and increase the number of DP moved to RLs.

The findings of this thesis are being provided to Cal EMA. *However, it is imperative to note that the results presented here depend entirely on the assumptions and input data (much of which had to be estimated).* Changes to these assumptions and/or inputs could have significant impact on the results. A natural extension of this thesis would be to perform a comprehensive sensitivity analysis to identify where changes could matter, or to look for changes that lead to worst-case disruptions to emergency response.

Future collaboration between Cal EMA and Naval Postgraduate School faculty and students could update the scenarios in this thesis with more accurate data. In addition, the POM can be used for disaster planning in other counties. Finally, a graphical user interface for data input and output would allow Cal EMA to easily modify and evaluate new cases more efficiently.

APPENDIX A. PREPOSITIONING OPTIMIZATION MODEL FORMULATION

This appendix describes the mathematical formulation for the POM model used in this thesis, as it appears in Salmeron and Apte (2010). The term "vehicle" used in the rest of this thesis is referred to as "means of transportation" (MoT) in this appendix.

Indices and Index Sets:

A Set of affected areas (AAs); $a \in A$

L Set of starting and drop off relief locations (RLs); $l \in L$

T Set of MoT (e.g., UH-1H aircraft, HMVV land-vehicle); $t \in T$

T_l Subset of MoT that can depart from (and drop off at) RL l

T^R Subset of MoT that require ramp space for delivery of commodities (aircraft assets)

Ω Set of disaster scenarios; $\omega \in \Omega$

Deterministic Parameters (units):

h_l^0, $h_l^{\max}$, c_l^H Initial capacity for health personnel at RL l (health care providers), maximum capacity expansion (health care providers), and variable expansion cost ($ / health care provider)

s^H EP that one health care provider can handle (persons)

s_l^0, $s_l^{\max}$, c_l^S Initial capacity for EP at relief location l (persons), maximum capacity expansion (persons), and variable expansion cost ($ / person). (These are based on the initial health personnel, maximum health personnel expansion, variable health personnel cost, and s^H)

r_a^0, $r_a^{\max}$, c_a^R Initial ramp space capacity at AA a (ft^3×1000), maximum capacity expansion (ft^3×1000), and variable expansion cost ($ / ft^3×1000), respectively

$m_l^0, m_l^{\max}, c_l^M$ Initial capacity for commodities at RL l (ft^3×1000), maximum capacity expansion (ft^3×1000), and variable expansion cost ($ / ft^3×1000), respectively

$u_t^0, u_t^{\max}, c_t^U$ Initial number of units of MoT t (vehicles), maximum capacity expansion (vehicles), and variable expansion cost ($ / vehicle), respectively

d_l^0, $d_l^{\max}$, c_l^D Initial shelter capacity for DP at RL l (persons), maximum capacity expansion (persons), and variable expansion cost ($ / person)

$\bar{s}_t$ Capacity for EP of special MoT t (persons / vehicle × trip)

$\bar{m}_t$, $\bar{w}_t$ Capacities for commodities ($\text{ft}^3 \times 1000$ / vehicle × trip) and relief workers (workers / vehicle × trip), respectively, of general MoT t

$\bar{d}_t$ Capacity for DP of general MoT t (persons / vehicle × trip).

h_t Available hours during the planning time for each unit of MoT t (hours / vehicle)

b Total budget allocated ($)

q Penalty for unmet commodities (i.e., q of the *stay-backs* are assumed to perish per unit of unmet commodities) (persons / $\text{ft}^3 \times 1000$)

α Relaxation level for the first objective when the second objective is optimized (fraction)

Scenario-dependent parameters (units), all under scenario ω:

m_a^ω Demand for commodities in AA a ($\text{ft}^3 \times 1000$)

s_a^ω EP in affected area a (persons)

λ_a^ω Survival rate for EP rescued in affected area a (fraction)

d_a^ω Number of DP in AA a (persons)

h_{tla}^ω Trip time (hours) for MoT t to travel from RL l to AA a (hours / trip). (The same time is assumed from a to l, so only h_{tla}^ω is defined.)

w_a^ω Relief workers required to handle commodities at AA a (workers / $\text{ft}^3 \times 1000$)

p^ω Probability of scenario ω occurring

Derived Sets:

L^S, L^M, L^D, A^R Subset of RLs, supply locations, shelter locations and AAs with ramp space, respectively. E.g., $L^S = \{l \in L \mid s_l^0 > 0 \text{ or } s_l^{\max} > 0\}$

T^G, T^S Subsets of general mission MoT (i.e., $\bar{s}_t = 0,\ \bar{m}_t \geq 0, \bar{w}_t \geq 0, \bar{d} \geq 0$) and special mission MoT (i.e., $\bar{s}_t > 0,\ \bar{m}_t = \bar{w}_t = \bar{d}_t = 0$), respectively.

K Subset of four-tuples (t, l, a, l') where MoT t can travel from l to a and then to l': $\{(t,l,a,l') \in T \times L \times A \times L \mid h^{\omega}_{tla} + h^{\omega}_{tl'a} \le \tau_t,\ t \in T_l \cap T_{l'}\}$, where τ_t is the operating range of t.

K^G, K^S Subsets of four-tuples (t, l, a, l') where general mission MoT t and special mission MoT t, respectively, can travel from l to a, and then to l':

$$K^G = \{(t,l,a,l') \in K \mid t \in T^G; l, l' \in L^M \cup L^D\};\ K^S = \{(t,l,a,l') \in K \mid t \in T^S, l' \in L^S\}$$

First-stage decision variables (units):

Δs_l	Expansion for health capacity for EP at drop off RL l (persons)
Δm_l	Expansion for commodities at RL l (ft^3×1000)
Δr_a	Expansion for ramp space at AA a (ft^3×1000)
Δd_l	Expansion for DP at relief location l (persons)

Second-stage decision variables (units), all under scenario ω:

Δu^{ω}_t	Additional units of MoT t needed (vehicles)
$S^{\omega}_{tlal'}$	EP rescued by MoT t traveling from l to a and then l' (persons)
S^{ω}_{ta}	Total EP rescued by MoT t at AA a (persons)
US^{ω}_a	Unmet EP at AA a (including rescued but not surviving) (persons)
$M^{\omega}_{tlal'}$	Commodities delivered by MoT t traveling from l to a and then l' (ft^3×1000)
M^{ω}_{ta}	Total commodities delivered by MoT t to AA a (ft^3×1000)
UM^{ω}_a	Unmet commodities at AA a (ft^3×1000)
$D^{\omega}_{tlal'}$	DP transported by MoT t traveling from l to a and then l' (persons)
D^{ω}_{ta}	Total DP transported by MoT t from AA a (persons)
UD^{ω}_a	Unmet transfer population at affected area a (persons)
$N^{\omega}_{tlal'}$	Number of trips from l to a and then to l' by MoT t (trips)
W^{ω}_{ta}	Number of relief workers carried by MoT t to AA a (workers)
z_1, z_2	Objective value for the first goal (persons) and second goal (persons), respectively

Formulation:

Objective 1 (minimize): Expected Casualties from EP and AP:

$$z_1 = \sum_{\omega} p^{\omega} \sum_{a} \left(US_a^{\omega} + qUM_a^{\omega} \right) \tag{1.1}$$

Objective 2 (minimize): Expected Unmet DP:

$$z_2 = \sum_{\omega} p^{\omega} \sum_{a} UD_a^{\omega} \tag{1.2}$$

Budget:

$$\sum_{l \in L^S} c_l^S \, \Delta s_l + \sum_{l \in L^M} c_l^M \, \Delta m_l + \sum_{l \in L^D} c_l^D \, \Delta d_l + \sum_{a \in A^R} c_a^R \, \Delta r_a + \sum_{t} c_t^U \, \Delta u_t^{\omega} \le b, \forall \omega \tag{2}$$

MoT Available and Trips:

$$\Delta u_t^{\omega} \le u_t^{\max}, \forall t, \omega \tag{3.1}$$

$$\sum_{(l,a,l')|(t,l,a,l') \in K} (h_{tla}^{\omega} + h_{tl'a}^{\omega}) N_{tlal'}^{\omega} \le h_t (u_t^o + \Delta u_t^{\omega}), \forall t, \omega \tag{3.2}$$

$$\sum_{(l',a)|(t,l',a,l) \in K} N_{tl'al}^{\omega} = \sum_{(a,l')|(t,l,a,l') \in K} N_{tlal'}^{\omega}, \forall l, t \in T_l, \omega \tag{3.3}$$

EP and Its Transportation:

$$\Delta s_l \le s_l^{\max}, \forall l \in L^s \tag{4.1}$$

$$\sum_{(t,a)|(t,l,a,l') \in K^S} S_{tlal'}^{\omega} \le s_l^o + \Delta s_l, \forall l, l' \in L^s, \forall \omega \tag{4.2}$$

$$S_{tlal'}^{\omega} \le \overline{s}_t N_{tlal'}^{\omega}, \forall (t,l,a,l') \in K^S, \forall \omega \tag{4.3}$$

$$S_{ta}^{\omega} = \sum_{(l,l')|(t,l,a,l') \in K^S} S_{tlal'}^{\omega}, \forall a \in A, t \in T^S, \forall \omega \tag{4.4}$$

$$\sum_{t \in T^S} \lambda_a^{\omega} S_{ta}^{\omega} + US_a^{\omega} = s_a^{\omega}, \forall a, \omega \tag{4.5}$$

$$\sum_{t \in T^S} S_{ta}^{\omega} \le s_a^{\omega}, \forall a, \omega \tag{4.6}$$

Delivery of Commodities for AP:

$$\Delta m_l \le m_l^{\max}, \forall l \in L^M \tag{5.1}$$

$$\sum_{(t,a,l')|(t,l,a,l') \in K^G} M_{tlal'}^{\omega} \le m_l^o + \Delta m_l, \forall l \in L^M, \forall \omega \tag{5.2}$$

$$M_{tlal'}^{\omega} \le \overline{m}_t N_{tlal'}^{\omega}, \forall (t,l,a,l') \in K^G, \forall \omega \tag{5.3}$$

$$M_{ta}^{\omega} = \sum_{(l,l')|(t,l,a,l') \in K^G} M_{tlal'}^{\omega}, \forall t \in T^G, \forall a, \omega \tag{5.4}$$

$$\sum_{t \in T^G} M_{ta}^{\omega} + UM_a^{\omega} = m_a^{\omega}, \forall a, \omega \tag{5.5}$$

Sheltering DP:

$$\Delta d_l \le d_l^{\max}, \forall l \in L^D \tag{6.1}$$

$$\sum_{(t,l,a)|(t,l,a,l') \in K^G} D_{tlal'}^{\omega} \le d_{l'}^o + \Delta d_{l'}, \forall l' \in L^D, \forall \omega \tag{6.2}$$

$$D_{tlal'}^{\omega} \le \overline{d}_t N_{tlal'}^{\omega}, \forall (t,l,a,l') \in K^G, \forall \omega \tag{6.3}$$

$$D_{ta}^{\omega} = \sum_{(l,l')|(t,l,a,l')\in K^G} D_{tlal'}^{\omega} \text{ , } \forall t \in T^G, \forall a, \omega \tag{6.4}$$

$$\sum_{t\in T^G} D_{ta}^{\omega} + UD_a^{\omega} = d_a^{\omega}, \forall a, \omega \tag{6.5}$$

Ramp Space:

$$\Delta r_a \le r_a^{\max}, \forall a \in A^R \tag{7.1}$$

$$\sum_{t\in T^R} M_{ta}^{\omega} \le r_a^o + \Delta r_a, \forall a \in A^R, \forall \omega \tag{7.2}$$

Relief Workers versus Commodities:

$$\sum_{t\in T^G} W_{ta}^{\omega} \ge w_a^{\omega} \sum_{t\in T^G} M_{ta}^{\omega}, \forall a, \omega \tag{8.1}$$

$$\bar{w}_t M_{ta}^{\omega} + \bar{m}_t W_{ta}^{\omega} \le \bar{w}_t \bar{m}_t \sum_{(l,l')|(t,l,a,l')\in K^G} N_{tlal'}^{\omega}, \forall t \in T^G, \forall a, \omega \tag{8.2}$$

Domain for Decision Variables:

$$\begin{aligned} &\Delta m_l,\ \Delta s_l,\ \Delta r_a,\ \Delta d_l,\ M_{tlal'}^{\omega},\ M_{ta}^{\omega},\ UM_a^{\omega},\ S_{tlal'}^{\omega},\ S_{ta}^{\omega}, \\ &US_a^{\omega},\ D_{tlal'}^{\omega},\ D_{ta}^{\omega},\ DM_a^{\omega} \ge 0, \quad \forall t, l, l', a, \omega \end{aligned} \tag{9.1}$$

$$\Delta u_t^{\omega},\ N_{tlal'}^{\omega},\ W_{ta}^{\omega} \ \ge 0 \text{ and integer, } \forall t, l, l', a, \omega \tag{9.2}$$

PO is a multi-objective model comprising two optimization problems hierarchically arranged. In the first one, PO-1, we minimize expected casualties resulting from non-rescued (and rescued but not surviving) EP and the AP casualties due to unmet commodities, as given by equation (1.1). The second model, PO-2, minimizes unmet demand for transfer population (1.2):

$$\text{PO-1: } z_1^* = \min z_1 \quad \text{s.t.} \begin{cases} (1.1) \\ (2)\text{-}(9.2) \end{cases}$$

$$\text{PO-2: } z_2^* = \min z_2 \quad \text{s.t.} \begin{cases} (1.2) \\ (2)\text{-}(9.2) \\ z_1 \le (1+\alpha) z_1^* \quad (10) \end{cases}$$

Notice that PO-1 might be seen as a bi-objective problem itself, since it seeks to meet the demand of two different groups of people. Our assumption is that both groups are equally important in the sense that failing to meet either demand results in persons to perish. Specifically, (1.1) accounts for casualties from the critical population, along with a fraction of those who do not receive commodities (q casualties per $\text{ft}^3 \times 1000$). PO-2 minimizes unmet demand for transfer population, but with the additional constraint (10) as an aspiration level based on PO-1's optimal solution. (In our test cases we set the aspiration level to $\alpha = 1\%$.)

All of the remaining constraints are shared by both models. (2) is the budget constraint. Most of the budget allocation is expected to occur during the first stage (expansion of medical facilities, warehouses, shelters, and ramp space). The remaining budget can be allocated to the engagement of additional MoT from the available fleet, usually commercial transportation, arranged beforehand to become available during a disaster, with contractual cost based on the level of utilization (thus, scenario-dependent). It is precisely these constraints that link decision variables involving critical population and commodities. Here, we note a possible enhancement would be to capture the influx of additional funding after the disaster has occurred. While part of this funding may be provided by private donors at the onset of a disaster for different purposes (such as financial help to individuals, reconstruction, etc.), we note that it is not complicated to accommodate an anticipated extra budget, b^{ω}, particular to each scenario, by simply adding b^{ω} to the right-hand side of equation (2). (This extension has not been explored in our experiments, i.e., we assume $b^{\omega}=0$ for each ω.)

Constraints (3.1) bound the maximum capacity expansion for MoT, whereas (3.2) ensure travel time per MoT does not exceed their available operating hours. Constraints (3.3) are flow-balance constraints in and out of each of RL. This is a global balance equation by MoT type, understanding that the actual schedule details of each individual vehicle, aircraft or vessel cannot be anticipated and would become an unnecessary complication for long-term planning purposes.

Constraints (4.1) limit the allowable increase in health care providers located in the respective RLs. Constraints (4.2) limit the amount of EP that can be treated by available health providers. Constraints (4.3) ensure these people are carried by a MoT configured for special mission, traveling on a given route, but not exceeding the capacity. Constraints (4.4) – (4.6) account for "met" and "unmet" demand of EP at each affected area. Specifically, the survival rate in (4.5) reflects that part of the EP rescued will perish.

Constraints (5.1) limit warehouse expansion. (5.2) limit delivery from eligible warehouses. (5.3) ensure the commodities are carried by existing MoT configured for general mission on each route. (5.4) and (5.5) account for met and unmet demand of commodities for the AP at each AA. Likewise, (6.1) – (6.5) are constraints for sheltering DP.

Constraints (7.1) and (7.2) restrict ramp space expansion, which in turn limits commodities delivered by aircraft. Constraints (8.1) ensure that relief workers arrive at the AAs at a given rate based on the amount of commodities supplied to each affected area. Constraints (8.2) depict total capacity of a MoT on a general mission as a linear function of relief workers and commodities.

Finally, (9.1) and (9.2) define the appropriate domains for the decision variables.

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APPENDIX B. BASELINE TRAVEL TIMES

This appendix describes the baseline travel times for vehicles between RLs and AAs. Each trip is assumed to take a minimum of 0.2 hours. Blank spaces indicate the trip is not possible.

	AA1	**AA2**	**AA3**	**AA4**	**AA5**	**AA6**	**AA7**	**AA8**
RL1	0.5	0.25	0.5	0.6	0.6	0.8	1	1
RL2	0.25	0.2	0.2	0.25	0.4	0.6	0.75	0.75
RL3	0.2	0.25	0.2	0.2	0.2	0.4	0.6	0.6
RL4	0.5	0.6	0.6	0.4	0.7	0.8	0.6	0.8
RL5	0.5	0.6	0.6	0.4	0.7	0.8	0.6	0.8
RL6	0.8	0.9	0.7	0.5	0.5	0.6	0.2	0.2
RL7	1	1.1	1	0.9	0.95	1	0.5	0.6
RL8	1.1	1.1	1	0.8	0.75	0.6	0.5	0.4
RL9								
RL10								

Table 28. Baseline travel times for UH1H

	AA1	**AA2**	**AA3**	**AA4**	**AA5**	**AA6**	**AA7**	**AA8**
RL1	2	1.5	2	2.5	2.5	2.75	3	3
RL2	1	0.8	0.3	0.8	0.6	0.8	1.5	1.5
RL3	0.5	0.5	0.2	0.5	0.4	1.5	1.5	1.5
RL4	1.5	2	1.75	1	1.5	1.75	2	2.25
RL5	1.5	2	1.75	1	1.5	1.75	2	2.25
RL6	2.5	2.25	2	1	1	1.5	0.25	0.4
RL7	3	3	2.5	2.25	2.5	2.75	1	1.25
RL8	3	3	2.5	2	1.75	2	1.25	1
RL9	0.5	0.5	0.2	0.5	0.4	1.5	1.5	1.5
RL10	0.75	0.75	0.25	0.5	0.2	0.5	1.25	1

Table 29. Baseline travel times for Truck18, Van48, Van28, Shuttle, Bus, and AST

	AA1	**AA2**	**AA3**	**AA4**	**AA5**	**AA6**	**AA7**	**AA8**
RL1	2.2	1.65	2.2	2.75	2.75	3.025	3.3	3.3
RL2	1.1	0.88	0.33	0.88	0.66	0.88	1.65	1.65
RL3	0.55	0.55	0.22	0.55	0.44	1.65	1.65	1.65
RL4	1.65	2.2	1.93	1.1	1.65	1.925	2.2	2.475
RL5	1.65	2.2	1.93	1.1	1.65	1.925	2.2	2.475
RL6	2.75	2.48	2.2	1.1	1.1	1.65	0.275	0.44
RL7	3.3	3.3	2.75	2.475	2.75	3.025	1.1	1.375
RL8	3.3	3.3	2.75	2.2	1.925	2.2	1.375	1.1
RL9	0.55	0.55	0.22	0.55	0.44	1.65	1.65	1.65
RL10	0.825	0.83	0.28	0.55	0.22	0.55	1.375	1.1

Table 30. Baseline travel times for HMMWV

	AA1	**AA2**	**AA3**	**AA4**	**AA5**	**AA6**	**AA7**	**AA8**
RL1								
RL2	0.2			0.2	0.3	0.45	0.563	0.563
RL3	0.2			0.2	0.2	0.3	0.45	0.45
RL4	0.375			0.3	0.525	0.6	0.45	0.6
RL5								
RL6								
RL7								
RL8	0.825			0.6	0.5625	0.45	0.375	0.3
RL9								
RL10								

Table 31. Baseline travel times for C130

	AA1	**AA2**	**AA3**	**AA4**	**AA5**	**AA6**	**AA7**	**AA8**
RL1								
RL2	0.2			0.2	0.24	0.36	0.45	0.45
RL3	0.2			0.2	0.2	0.24	0.36	0.36
RL4	0.3			0.24	0.42	0.48	0.36	0.48
RL5								
RL6								
RL7								
RL8	0.66			0.48	0.45	0.36	0.3	0.24
RL9								
RL10								

Table 32. Baseline travel times for C17

	AA1	**AA2**	**AA3**	**AA4**	**AA5**	**AA6**	**AA7**	**AA8**
RL1								
RL2	0.2			0.2	0.3	0.45	0.563	0.563
RL3	0.2			0.2	0.2	0.3	0.45	0.45
RL4	0.375			0.3	0.525	0.6	0.45	0.6
RL5								
RL6								
RL7								
RL8	0.825			0.6	0.5625	0.45	0.375	0.3
RL9								
RL10								

Table 33. Baseline travel times for HC130

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