NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

ESCAPE FROM THE DELTA: PREPARATION AND EVACUATION FOR CATASTROPHIC FLOODING IN CALIFORNIA EMERGENCY MANAGEMENT AGENCY REGION IV

by

Timothy C. Yuhas

March 2011

Thesis Advisor:	David Alderson
Second Reader:	Matthew Carlyle

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704–0188

1. REPORT DATE *(DD–MM–YYYY)*
29–3–2011

2. REPORT TYPE
Master's Thesis

3. DATES COVERED *(From — To)*
2009-03-01—2011-03-31

4. TITLE AND SUBTITLE
Escape From the Delta: Preparation and Evacuation for Catastrophic Flooding in California Emergency Management Agency Region IV

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Timothy C. Yuhas

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES
The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. **IRB Protocol Number: N/A**

14. ABSTRACT

We model the regional highway system of Central California and consider the challenge of evacuating a highly populated region from the threat of catastrophic flood. Specifically, we build a minimum cost network flow problem to represent the movement of more than one million people within Yolo, Sacramento, San Joaquin, and Stanislaus Counties. Our model solves for "best case" evacuation routes and clearing times assuming perfect knowledge of flood inundation and road conditions. Our model is large but efficient, solving 35 separate scenarios in less than 45 minutes. We develop two basic evacuation scenarios, each having many variations, resulting in 490 total scenarios. For these, we analyze model assumptions and the effect of interruptions to evacuation behavior for a range of "what-if" situations.

15. SUBJECT TERMS
Evacuation, Network Flow Optimization, Minimum Cost Network Flow

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
Unclassified	Unclassified	Unclassified	UU	83	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 8–98)
Prescribed by ANSI Std. Z39.18

THIS PAGE INTENTIONALLY LEFT BLANK

ESCAPE FROM THE DELTA: PREPARATION AND EVACUATION FOR CATASTROPHIC FLOODING IN CALIFORNIA EMERGENCY MANAGEMENT AGENCY REGION IV

Timothy C. Yuhas
Lieutenant, United States Navy
B.A., The University of Arizona, 2005

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
March 2011

Author: Timothy C. Yuhas

Approved by: David Alderson
Thesis Advisor

Matthew Carlyle
Second Reader

Robert Dell
Chair, Department of Operations Research

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

We model the regional highway system of Central California and consider the challenge of evacuating a highly populated region from the threat of catastrophic flood. Specifically, we build a minimum cost network flow problem to represent the movement of more than one million people within Yolo, Sacramento, San Joaquin, and Stanislaus Counties. Our model solves for "best case" evacuation routes and clearing times assuming perfect knowledge of flood inundation and road conditions. Our model is large but efficient, solving 35 separate scenarios in less than 45 minutes. We develop two basic evacuation scenarios, each having many variations, resulting in 490 total scenarios. For these, we analyze model assumptions and the effect of interruptions to evacuation behavior for a range of "what-if" situations.

THIS PAGE INTENTIONALLY LEFT BLANK

Table of Contents

1 Introduction **1**
1.1 History 2
1.2 Mitigation Efforts 4
1.3 The Challenge 6
1.4 Purpose 6

2 Literature Review **9**
2.1 When Do People Leave? 9
2.2 Where Do Evacuating Populations Go? 9
2.3 By What Means Do Evacuees Travel? 10
2.4 How Does Capacity Influence Evacuations?. 10
2.5 How Do Analysts Represent Highway Traffic?. 11

3 Evacuation Model **13**
3.1 Notation 13
3.2 Building the Network 14
3.3 Model Assumptions 16
3.4 Formulation 19

4 Analysis **25**
4.1 Establishing the Base Case 25
4.2 SCENARIO: Sacramento County 25
4.3 SCENARIO: River-Side Evacuation 34
4.4 Is Contraflow Worth the Effort? 40
4.5 Insights 41

5 Conclusion **45**
5.1 Summary 45
5.2 Recommendations 46

5.3 Future Work 46
5.4 Final Thoughts 47

Appendix

A Additional Data Tables **53**

Initial Distribution List **63**

List of Figures

Figure 1.1 The watershed which feeds the delta drains the majority of California's rainfall and snow melt (Bass, 2011) 1

Figure 1.2 Historic flood patterns over the delta region. (Gaddie et al., 2007) . . . 2

Figure 1.3 California Emergency Management Agency Region IV. 5

Figure 3.1 Dumbell graph representation illustrating flow from node p to node q. . 13

Figure 3.2 State and Federal Highways in Yolo, Sacramento, San Joaquin and Stanislaus counties. Dashed lines are TIGER data set, solid lines are CALTRANS data. 15

Figure 3.3 Two crossing arcs without interaction (A), junction representation (B) 16

Figure 3.4 Map with constructed network overlaid on the highways in Region IV. 17

Figure 3.5 Final road network with ZIP codes. 18

Figure 4.1 With no contraflow available to increase the rate that people depart, the importance of carpooling becomes clear. The legend notation depicts the number of passengers per vehicle followed by the number of contraflow miles used. 28

Figure 4.2 This depicts the capacity utilization of the various highways in the region as Sacramento County evacuees depart the region in the first epoch. . . 30

Figure 4.3 Evacuation clearing times comparing the use of contraflow combinations with various passenger combinations. The greatest benefit of contraflow comes when evacuees are one to a vehicle. As PPV increases the benefit of contraflow decreases. 31

Figure 4.4 The rate that evacuees reach available evacuation points drops by over 100,000 people/hour if PointsE are lost as an evacuation location. Evacuation times increase six hours as a result for PPV=2, 18 hours for PPV=1. 32

Figure 4.5 The optimal use of contraflow can hinder evacuations. Here CFM=50 causes an increase in clearing times in the PPV=1 scenario. Again, contraflow provides the greatest assistance to clearance times in the PPV=1 scenario with the use of CFM=200. 33

Figure 4.6 Here we observe that the rates of evacuees in the PPV=4 case evacuates almost 100,000 more people per epoch than the loss of PointsE scenario, but rates remain below the evacuation rate of the base case. 34

Figure 4.7 Again the addition of contraflow provides only a three hour improvement on evacuation times in the PPV=2 case. 35

Figure 4.8 Sacramento County evacuees flow through the highway network with the loss of PointsE in epoch one prior to the inundation of I-5. 36

Figure 4.9 Sacramento County evacuees detour around inundated highways and most of those detoured evacuate South. 37

Figure 4.10 Evacuation rates for the River-Side evacuation show an amazing increase in the number of people able to evacuate per epoch. PPV=2 increases by 100,000 people per epoch compared to the Sacramento County evacuation. 38

Figure 4.11 Contraflow results for the River-Side base case evacuation. This graph shows that contraflow only helps in some scenarios and only eases clearing times by three hours. 38

Figure 4.12 Evacuation rates for PPV=2 decrease by 100,000 people per epoch compared to the base case and increase clearing times by six hours. 39

Figure 4.13 Evacuation rates for PPV=2 decrease by 50,000 people per epoch compared to the base case and increase clearing times by six hours. 39

Figure 4.14 Contraflow does not significantly improve River-Side evacuation clearing times in the event of the Bay Area being cut off to evacuees. 40

Figure 4.15 The baseline Sacramento County scenario. We add two cuts. 42

Figure 4.16 The affects of these two cuts are evident in the resulting figure, all ability to evacuate to the North is severed. 43

List of Tables

Table 1.1 Fridirici & Shelton Table 1. 4

Table 4.1 Example of output for evac_sp_tot.csv. The last column indicates the table continues to the right, one column per additional epoch. 27

Table 4.2 Summary of evacuation results by evacuation point (in percentage and population) assuming PPV=2 and CFM=0. In these scenarios all evacuees were able to evacuate. 29

Table 4.3 Evacuation capacity from Yolo, Sacramento, San Joaquin, & Stanislaus counties into each of the evacuation points per hour. 42

Table A.1 node_location.csv data (headers provided for context) 53

Table A.2 node_location.csv data continued (headers provided for context) 54

Table A.3 node_location.csv data continued (headers provided for context) 55

Table A.4 node_location.csv data continued (headers provided for context) 56

Table A.5 node_location.csv data continued (headers provided for context) 57

Table A.6 Tables of Sacramento County evacuation duration case-by-case for every scenario. 58

Table A.7 Tables of Sacramento County evacuation duration case-by-case for every scenario continued. 59

Table A.8 Tables of River-Side ZIP code evacuation duration case-by-case for every scenario. 60

Table A.9 Tables of River-Side ZIP code evacuation duration case-by-case for every scenario. 61

Table A.10 g.csv data (headers provided for context) 61

Table A.11 inundation_schedule.csv data (headers provided for context) 62

Table A.12 evaclist.csv data (headers provided for context) 62

List of Acronyms and Abbreviations

ARkStorm	Atmospheric River Times 1,000 Storm
CA-99	California Highway 99
CA-120	California Highway 120
CAL EMA	California Emergency Management Agency
CALFED	CALFED Bay-Delta Program
CALTRANS	California Department of Transportation
CFM	Contraflow Miles
CHP	California Highway Patrol
DCP	Detailed Capacity Plan
ECAP	Evacuation Control and Assistance Points
EEP	Enforced Evacuation Plan
GAMS	General Algebraic Modeling System
GIS	Geographical Information Software
I-5	Interstate Highway 5
OES	California Office of Emergency Services
PPV	Passengers Per Vehicle
RCCP	Rough Cut Capacity Plan
REP	Restricted Evacuation Plan
SAFCA	Sacramento Area Flood Control Agency
SOP	Standard Operating Procedure
TIGER	Topologically Integrated Geographic Encoding & Referencing system
USGS	United States Geological Survey
ZIP	Zone Improvement Program

THIS PAGE INTENTIONALLY LEFT BLANK

Acknowledgements

I’ve been blessed to have had many great teachers in my life. A word (or two) of thanks to but a few who have helped me through this work. . .

- To my wife **Zoe**, like a lighthouse at dusk, you have always lit my world. Thanks for leaving the lights on for me and for being a guiding light for our daughter. I love you both.
- To my amazing parents **Rex** and **Debbie Yuhas**, you set the standard early and inspired us to go beyond. Words cannot capture the depth of my love and gratitude for all you have done. **Craig Yuhas**, my brother, you are an amazing man. I’m proud to be your brother. I love you.
- To the best Editor and Mathmagician I know; my Mother- and Father-in-law **Katherine** and **Dr. Randy Ott**, thank you for all the red ink and all the practice problems over Skype. Could not have done it without you.
- To my first math tutor Pythagoras, aka my Grandfather, **Ed Martin**, thanks for everything but most of all inspiring my love of learning. I will never forget you dressed in a toga, skipping with a little kid around a garage teaching me that a “minus times a minus is a positive!”
- To **CDR Matt Fleming**, thank you for the tip to look into Operations Research.
- To **Dr. David L. Alderson**, thank you for your help, mentorship and encouragement. Working with you was the highlight of my time at NPS.
- To **Dr. Matthew Carlyle**, thank you for bringing me to the world of Networks.
- To **Dr. Gerald Brown**, thank you for your expert GAMS assistance and patience.
- To **Ms. Wendy Walsh** for all of your amazing help in organizing contacts and making the introductions that made this thesis possible.
- To **Mr. Jim Brown**, and **Ms. Dana Owens** from California Emergency Management Agency Region IV, as well as **Mr. Ron Baldwin**, San Joaquin County Office of Emergency Services, thank you for the inspiration of this topic and working with us to develop a model that will aid regional emergency planners to understand future evacuations.

- To **Mr. Tremain Downey**, and **Mr. Navneet Singh** with California's Department of Transportation for providing an excellent set of highway data which made this all possible.
- And last but not least, to those to whom teaching is a life-long passion, you set a standard few meet, and even fewer exceed. To **Ms. Barbara Burns**, **Ms. Sandy Crane**, and **Mrs. Donna Foglia** on behalf of all your students, you truly are a National Treasure, thank you.

Executive Summary

We model the evacuation of inhabitants of Yolo, Sacramento, San Joaquin and Stanislaus Counties of Central California using a minimum cost network flow model of the regional highway system. Our model MINATRISK solves for "best case" evacuation routes and clearing times assuming perfect knowledge by all travelers of road conditions. Our model is large, but efficient, solving 35 separate scenarios in less than 45 minutes. By solving separate scenarios, we analyze model assumptions and the effect of interruptions to evacuation behavior for a range of "what-if" situations.

We develop two models to identify optimal evacuation routes as well as quantify highway demands during an evacuation in Yolo, Sacramento, San Joaquin and Stanislaus counties. MINATRISK is a single commodity minimum cost network flow model, and MINDIST is a shortest path optimization model which identifies the shortest path from every node in the network to every one of the possible evacuation points. We represent the system of highways in Region IV as a network, with ZIP codes representing sources of evacuees, transshipment nodes as highway junctions, and arcs as highway segments.

We establish a base case evolved from California Highway Patrol's Standard Operating Procedure which does not currently plan for contraflow, and apply this case to two baseline scenarios one in which Sacramento County is evacuated, and one in which ZIP codes which lie adjacent to the rivers of the region are evacuated. These scenarios differ only in the subset of ZIP codes which are directed to evacuate in the first epoch. Our model indicates that it is possible to evacuate approximately 1.2 million people from Sacramento County and River-Side evacuations in 24-hours and 15-hours respectively. We find that the shortest route for most evacuees is to travel to evacuation locations to the East and in the Bay Area. We find that loss of access to the evacuation points east of the valley increases evacuation clearing times by 25% in the Sacramento County scenario and 40% in the River-Side scenario.

We adjust parameters in the model to cause highway inundations and allow for the use of contraflow. Inundating highways did not substantially change evacuation results however, the inundation of I-5 combined with the loss of evacuation point "PointsE" did cause more people to travel to evacuation point "PointsS" in the River-Side evacuation than in any other scenario. Furthermore, because we assume two passengers per vehicle, we find people evacuate six hours faster with the use of contraflow. However, because the evacuation of Sacramento County in its entirety is unlikely, and the River-Side evacuation more plausible, we find that our model and the analysis of its results does not support the establishment of contraflow if the evacuating population is not concentrated as in the Sacramento County case.

Our model results show, for each scenario, the number of frustrated travelers in every time period over the planning horizon, and therefore paints a clear picture of the progress of the evacuation in each scenario. An important first step in understanding evacuations, the results of our model can provide insights to emergency planners for the positioning of supplies, determining emergency locations, and personnel requirements.

CHAPTER 1:
Introduction

Water, an undeniable necessity of life and a highly prized resource, at times is also a catalyst for vast destruction and death. The Sacramento-San Joaquin river delta, located in the northwest portion of California's Central Valley, drains more than 700,000 acres into the San Francisco Bay via 700 miles of waterways and approximately 1,100 miles of levees CALFED Bay-Delta Program (CALFED) (2000). Three major rivers, fed by an enormous watershed (see Figure 1.1), converge and drain through the delta: The American and Sacramento rivers (with the added flow of the Feather River and the Yuba River) drain from north to south, while the San Joaquin River and its tributaries drain from south to north. Normal flows combined with "intense rainfall,

Figure 1.1: The watershed which feeds the delta drains the majority of California's rainfall and snow melt (Bass, 2011)

rapid snowmelt, or a combination of these weather-related events are the common causes of Central Valley floods" (Fridirici & Shelton, 2000). As a result of this threat, it is not uncommon to see homes in the region built on stilts to raise their elevations above sea level as an added protection against levee failure. Figure 1.2 shows the historic impact of flooding on the delta. Consequently, for many residents who reside within the delta the risk of flood is a part of everyday life.

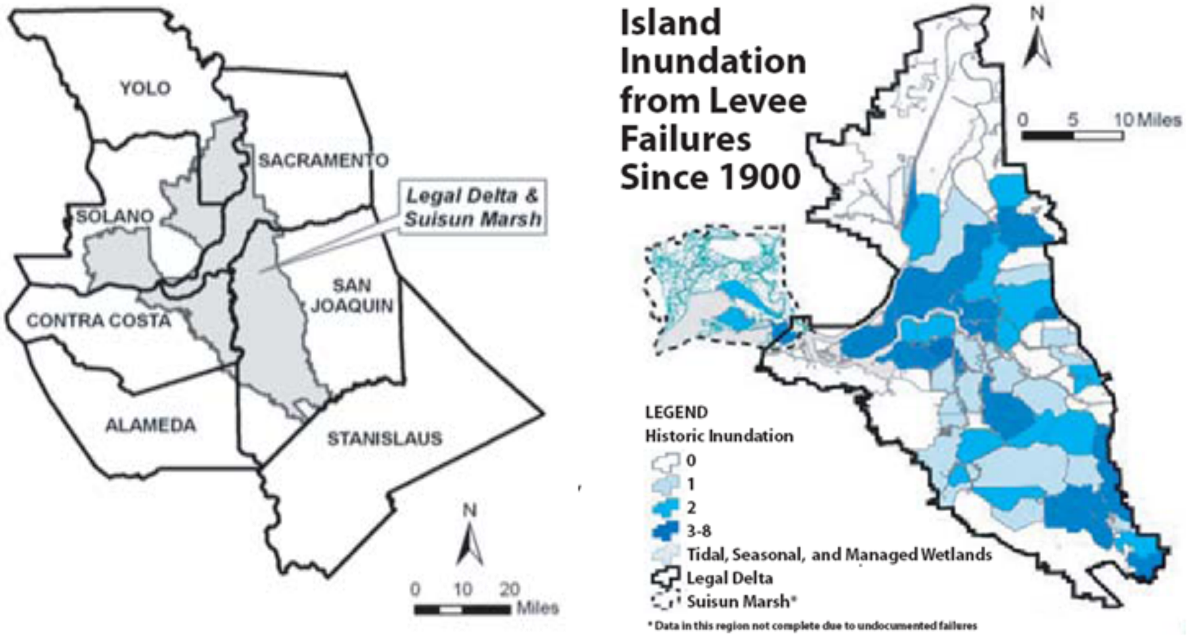


Figure 1.2: Historic flood patterns over the delta region. (Gaddie et al., 2007)

1.1 History

Within 11 years of its founding, the city of Sacramento faced its first two floods, followed 11 years later by the great 1861–1862 flood. With water flowing over the top of levees built in the preceding decade, parts of Sacramento sat 20 feet below water, resulting in Governor-elect Leland Stanford being transported to his inauguration in a row boat (Center For Sacramento History, 2004). Over the next 90 years, the region experienced only mild flooding until new records were set in 1951. Between 1951 and 1997, the region experienced five record-setting floods, culminating in the major 1997 flood, which killed eight people and caused approximately $1.95 billion in damage (Fridirici & Shelton, 2000).

Major floods in this region are typically generated by two different types of storms that occur during an El Niño season. One of the two types is caused by the cold arctic fronts that primarily deliver snow to mid and high elevations across the state. In a normal season, this snow melts during late spring and into the summer months gradually feeding runoff into the river system. The second type, known as a "Pineapple Express" storm, is much warmer and originates in the Pacific, delivering snow only to the highest elevations and extreme rain to all other elevations. These warm storms not only cause small stream floods just from rainfall but can increase snow melt at elevations which are not cold enough to form this precipitation into snow.

This was the scenario in the winter of 1996–1997, when cold front-driven storms moved into California delivering the "second wettest December since 1922, when records began for the Northern Sierra" (Fridirici & Shelton, 2000). This storm not only delivered inches of rainfall to lower elevations but also packed the Sierra-Nevada Mountain range with deep snow. On 26 December 1996, a Pineapple Express storm hit California and lingered until 2 January 1997, its seven-day downpour, combined with the five days of rain preceding the Pineapple Express, delivered 47.6 inches of rain, 40% of a normal rain year, and melted previously deposited snow at lower elevations (Fridirici & Shelton, 2000). The moisture from this series of storms produced the wettest two consecutive months in California's history. Within days, reservoirs that were expected to take weeks to fill were forced to release as much water as possible within their design specifications. For some dams, it was still not enough.

On 2 January 1997, Don Pedro Dam on the San Joaquin River reached its maximum capacity "and water spilled over the emergency spillway. Releases from the dam measured 59,000 cfs [cubic feet per second]" (Fridirici & Shelton, 2000). Downstream in Modesto, at the Ninth Street Bridge, the in-stream flow was six times normal capacity. Don Pedro was only one example of dams exceeding capacity and releases exceeding design specifications. This regional problem resulted in downstream flows greater than the levees were designed to hold. With increased flows, the flood levels set seven high-water records (see Table 1.1). As a result, 36 Federal Project levees failed on the San Joaquin River and 12 failed on the Sacramento River. These failures flooded vast tracts of land which eased flows further downstream where the flows fell within designed levee capacities but at the cost of over $1billion in damage.

By 9 January 1997, the worst of the damage was done, and most of the flood waters started to recede. The tally of damaged and destroyed property: 12,792 residences, and 1,752 businesses. Over the course of the 12-day storm, more than 120,000 people were evacuated (Mullins et al., 1997), with most of the evacuees originating from San Joaquin and Stanislaus counties.

Table 1.1: Fridirici & Shelton Table 1.

Selected Flood Peaks for 1998, 1997, & 1986 (feet)					
River	Station	Feb. 1998	Jan. 1997	Feb. 1986	Previous Record
Sacramento	Above Bend Bridge	27.9	30.6	32.8	36.6 Jan. 1970
	Ord Ferry	118.2	118.7	118.3	119.8 Jan. 1970
	Colusa	68.3	68.6*	68	68.5 Mar. 1983
	Fremont	38.5	42.5*	41.7	41.7 Feb. 1986
	Sacramento, I St.	25.2	30.4	30.7*	30.7 Feb. 1986
Feather	Yuba City	54.9	78.2*	76.3	76.3 Feb. 1986
	Nicolaus	n/a	50.4*	49.1	49.1 Feb. 1986
American	H Street	33.4	42.7	43.4*	43.4 Feb. 1986
Cosumnes	Michigan Bar	13.2	18.3*	14.8	14.8 Feb. 1986
Tuolumne	Modesto	56.6	70.9*	55.2	69.2 Dec. 1950
San Joaquin	Newman	64.6	66.1*	64.7	65.9 Feb. 1969
					* New Record

1.2 Mitigation Efforts

History shows that flooding in this region can potentially affect hundreds of thousands of people within a short period of time. After the 1862 flood, Sacramento residents began an aggressive campaign to build levees, redirect rivers, and create weirs and bypass channels in an attempt to prevent future major floods (Sacramento Area Flood Control Agency (SAFCA), 2008). The cycle of flood and restoration, followed by the building of preventive infrastructure, defines the region, but despite ongoing efforts, floods continue to ravage the area.

Since the 1997 flood devastated this region, organizers from neighboring counties recognized the need for regional support. A flood event that required relatively few evacuations could be handled by the local jurisdictions; however, no structure existed to support neighboring counties in the event of a need to evacuate a substantial portion of a regional population. Starting in 2000, the directors of the California Office of Emergency Services for the counties affected by the 1997 flood held a series of meetings to address this problem (Baldwin, 2010). After three years of meetings, officials developed the “Inland Region Mass Evacuation System Operations Manual” (Baldwin, 2006a) and its counterpart for local jurisdictions, “Local Government Guide to Inland Region Mass Evacuation System” (Baldwin, 2006b). These documents called for a regional coordinating agency with authority to direct county resources during a regional mass evacuation scenario.

Established in 2009, almost seven years after completion of the documents which called for its creation, the California Emergency Management Agency (CAL EMA) stood up.

> CAL EMA is responsible for the coordination of overall state agency response to major disasters in support of local government. The Agency is responsible for assuring the state's readiness to respond to and recover from all hazards — natural, manmade, war-caused emergencies and disasters — and for assisting local governments in their emergency preparedness, response, recovery, and hazard mitigation efforts. (California Office of Emergency Services (OES), 2011a)

CAL EMA divides responsibilities for supporting local counties across several administrative regions. To be better prepared for this and other threats, the state of California divided itself into several Emergency Management Mutual Aid Regions (see Figure 1.3 at left). Region IV, the focus of our analysis, is comprised of 11 counties (see Figure 1.3 at right), and home to 3.5 million people. Four counties in Region IV, Yolo, Sacramento, San Joaquin, and Stanislaus counties experienced the wrath of the 1997 flood. Together they house 78% of the population or 2.8 million people (U.S. Census Bureau, 2000). Region IV administrators are responsible for

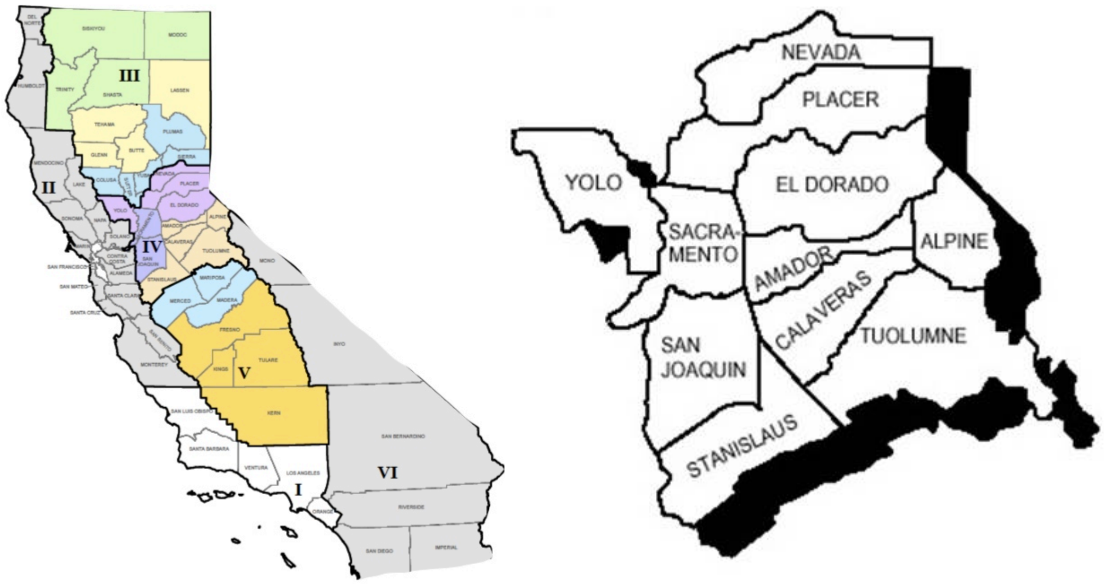


Figure 1.3: California Emergency Management Agency Region IV.

coordinating and assisting with emergency situations which impact multiple counties. As such it enhanced the recommendations of the "Local Government Guide to Inland Region Mass Evacuation System Operations Manual" (Baldwin, 2006a) and implemented the plan for a regional evacuation system. The result is a streamlined foundation for multi county, inter-jurisdictional operations with the intent of "coordinating traffic control, evacuee roadside assistance on major evacuation corridors, [and] coordinated shelter information for evacuees" (California Office of Emergency Services (OES), 2010).

1.3 The Challenge

Towns and highways have a co-evolving, dependent relationship. Towns grow along highway routes, and in turn regional planners expand highway capacity in response to increased demand for travel by the local population. Modern highways are designed to handle the anticipated needs of travelers during normal traffic patterns (*e.g.,* daily commuting). These patterns typically involve a diversity of destinations, resulting in traffic moving several directions at once. However, in a mass evacuation scenario, the population has, generally speaking, the same evacuation destination(s), resulting in a concentration of traffic along the same routes. If a large number of people are forced to evacuate an area, highways quickly exceed their designed capacities, and the rate of vehicles slows because of *congestion*. The inability to move people along a given route has a significant impact on the amount of time to evacuate a population, known as the *clearing time*.

Even in a moderate flood, the highways that run north and south through California's Central Valley are likely to become inundated by rising water levels at some point. For example, Interstate Highway 5 (I-5) and California Highway 99 (CA-99) were closed in sections or reduced to one lane as a result of flooding in 1997. This scenario leaves the east-west highways as the possible evacuation routes for the people who live in Yolo, Sacramento, Stanislaus, and San Joaquin counties. The risk of catastrophic flood to the region and its impact is widely recognized by State and Federal government officials, who selected this flooding scenario as the focus of the 2011 Golden Guardian statewide emergency planning and response exercise (California Office of Emergency Services (OES), 2011b).

1.4 Purpose

The purpose of any evacuation model is to assess the ability to evacuate a target population from a given area in an adequate amount of time. In essence, one needs to compute the total time to evacuate the last person from the at-risk area. However, viewing this region and the resulting evacuation from the perspective of a network flow problem enables a much more in-depth analysis of the evacuation and the impacts it will likely have on the entire region. We consider several factors: potential evacuation routes for an at-risk population, the capacity constraints affecting evacuation times, and whether evacuation route planning can relieve evacuation times. Also, we calculate the average distance evacuees travel as well as identify possible bottlenecks in the network. Finally, we track the flow of vehicles into and out of each county over the various routes to provide emergency planners an estimate of the number of evacuees expected to travel through their county. Although Region IV is staffed with emergency planners possessing decades of experience, an essential requirement for successful planning, the analysis generated by this thesis is intended to provide planners key insights into how evacuation plans may be further refined.

In the next Chapter, we review recent and current research on evacuations and describe the methods used to develop evacuation plans. We then present our models in Chapter 3 followed by our analysis in Chapter 4. Finally, we give our recommendations and opportunities for future work based on our analysis in the final Chapter.

THIS PAGE INTENTIONALLY LEFT BLANK

CHAPTER 2:
Literature Review

A large body of academic literature exists on the study of evacuations. Yusoff, Ariffin, & Mohamed (2008) illustrate the diversity of this field in their broad survey of evacuation models. This chapter provides a partial review of relevant work in order to place our contribution in broader context, as well as describe how others in the field conduct similar efforts. For our purposes, several factors affect the behavior of an evacuation. For each, we summarize key features and describe how we address them in our analysis.

2.1 When Do People Leave?

Time is of the essence in an evacuation. To obtain a sufficient measure of how long an evacuation takes, we must understand how an at-risk population responds when notified to evacuate. Sorensen (1991, p. 154) argues that people react to an evacuation warning in accordance with a logistic distribution. Garcia, Llinares, Marrero, Ortiz, & Rodriquez-Losada (2010) also use a statistical distribution to describe the "panic-factor" that some people experience when faced with an emergency. Santos & Aguirre (2005, p. 43) argue that "people [do] not panic" but rather act with clarity and decisiveness when faced with an evacuation. This argument coincides with Sorensen (1991, p. 162) who concedes that despite dozens of studies over 25 years, "analysis provides only a sketchy answer" with regard to how people react when notified to evacuate.

We do not account for any panic factors in our modeling. Sorensen (1991) makes clear that despite any initial delay, panic appears to be event-specific, but is measured in minutes. We make the simple assumption that if our population is able to leave their starting location, they do so by the end of the first time epoch (a matter of hours or days) in which they have been ordered to evacuate. An *epoch* is a flexible duration of time at the end of which, our model reviews the state of the evacuation.

2.2 Where Do Evacuating Populations Go?

Understanding where people go when they leave can be just as important as recognizing the need to evacuate. Two possibilities are that the population travels to the closest evacuation point (to minimize clearing time) or that they head toward a specific evacuation destination (*e.g.,* because they have friends and/or family there). The routes they take will affect how long it takes them to get to the evacuation destination. In some cases, individuals decide their own routes based on availability, while in other cases, local officials pre-plan emergency routes.

Ardekani, Assavapokee, & Lahmar (2006) present a four-tiered evacuation model to assess evacuations in the hurricane prone region of the southeastern United States. Their first-stage evacuation model assesses the over-all feasibility of the evacuation in terms of time. This model, known as the "Rough-Cut Capacity Plan" (RCCP), measures the amount of time it takes to evacuate an at-risk population in a manner that minimizes the overall evacuation time. Second, they develop a model based on the population being able to evacuate within a specific time window. The "Detailed Capacity Plan" (DCP) evaluates the evacuation given preferred safe destinations for evacuees. Third, they create the "Restricted Evacuation Plan" (REP) model used to explore back-up evacuation plans if the RCCP is not feasible. Finally, in the event that the DCP is not feasible, they use the "Enforced Evacuation Plan" (EEP) to "evaluate alternative strategies that enforce specific safety destinations" (Ardekani et al., 2006, p. 616).

We model evacuation behavior where evacuees evacuate to any safe destination in a manner which minimizes distance traveled. We do not constrain the routes available to the evacuees; however, we do conduct "what-if analysis" surrounding the loss of specific highway routes.

2.3 By What Means Do Evacuees Travel?

Renne, Sanchez, & Litman (2008) present an overview of the issues associated with multimodal (*e.g.,* carless) evacuation by populations with special needs. Chapter 2 of that report provides a review and taxonomy for different disaster types. In this thesis, we ignore the need to evacuate populations by means other than personally owned vehicles; that is, we assume that everyone has the ability to drive in either their own vehicles or in a vehicle of someone they know.

2.4 How Does Capacity Influence Evacuations?

Highway capacity is a major limiting factor in the amount of time it takes to evacuate a population, particularly because demand along individual highway segments during an evacuation can greatly exceed normal travel conditions. In some cases, Emergency Services can augment highway capacity by opening both sides of a highway, which travel in opposing directions under normal circumstances, to traffic traveling in one direction. This technique is known as *contraflow*. As noted by Xie, Waller, & Kockelman (2011), "in evacuation cases, the traffic direction of inbound lanes along some designated roadways may be reversed to better accommodate outbound traffic" (2011, p. 2).

When faced with large-scale disasters, cities in the Gulf Coast region of the United States have used contraflow effectively. Xie, Waller, & Kockelman (2011) review a dense history of analysis pertaining to the use of contraflow. They consider not only contraflow but also minimizing instances of cross traffic flow (*e.g.,* at intersections) to improve evacuation capacity.

The feasibility of using contraflow within CAL EMA Region IV is a hotly debated subject. We use our model to quantify the potential differences in evacuation behavior when contraflow is used, including obeying specific restrictions on where and how much contraflow can be used.

2.5 How Do Analysts Represent Highway Traffic?

Finally, the way in which traffic is represented in an evacuation is a major contributing factor in the decision on how to model an evacuation. In an evacuation which uses highways, vehicles are the primary means of conveying the population to safety. Assumptions about the relationship between traffic and highway capacity can impact the modeling one uses to analyze an evacuation. There are two primary ways of approaching this challenge.

2.5.1 Microscopic Models

The first type of model starts with a belief that individual vehicles and their interactions or behaviors have an impact on the overall evacuation; these assumptions result in what is known as a *microscopic model*. "These models usually consider detailed individual parameters such as traveling speed, reaction time, and interaction outcomes of each evacuee with others during the evacuation" (Ardekani et al., 2006, p. 613). Examples of microscopic evacuation models include Langford (2010) and some of the work reviewed in Santos & Aguirre (2005), but there are important differences.

Mathematical programming formulation

One approach starts with an equation-based description of known relationships among system states and events, which are often expressed in terms of objectives and constraints. These can be deterministic or stochastic, and the goal of any individual formulation is to obtain a solution that is not only feasible (*i.e.,* satisfying all constraints) but also is provably better than the others. Langford (2010) is not concerned with the sociological factors that impact evacuation; his primary concern is how individual vehicles traverse a road network in an evacuation. Langford illustrates how a network flow model can be used to model a microscopic level of detail without incorporating complications such as human behavior.

Simulation-based formulations

Simulation techniques are convenient for studying systems where sociological factors are involved because these factors are difficult to quantify mathematically. Law (2007, p. 5) explains that if a problem is so complex that it cannot be solved deterministically then, “the model must be studied by means of simulation, i.e., numerically exercising the model for the inputs in question to see how they affect the output measures of performance.” Santos & Aguirre provide examples that use agent-based simulation to capture many such factors, which are often modeled using “if-then” statements rather than aggregate equations.

2.5.2 Macroscopic Models

Macroscopic models typically evaluate evacuations as aggregate flows and do not account for behavior on the individual level. These models “can produce tight lower bounds on the expected evacuation time and upper bounds on the number of people successfully evacuated” (Ardekani et al., 2006, p. 613). Ardekani et al. (2006) use a macroscopic approach to hurricane evacuations, and Yusoff et al. (2008) survey the strengths and weaknesses of various types of macroscopic models. As above, these models also consist of both mathematical programming and simulation formulations. Specifically, evacuation models presented by Ardekani et al. (2006) use network flows to analyze hurricane evacuations, and Yusoff et al. (2008) provide examples of macroscopic simulation models used for analyzing evacuations.

We present a macroscopic, mathematical programming formulation approach that focuses on the evacuation at a strategic level in which vehicles are modeled as aggregate flows. We assume congestion is reflected by the road capacity specified for a given segment of highway.

CHAPTER 3:
Evacuation Model

To model a regional system of highways, we develop a network flow model. Ahuja, Magnanti, & Orlin (1993, p. 24) define a network as "a graph whose nodes and/or arcs have associated numerical values (typically, costs, capacities, and/or supplies and demands." Networks exist in many forms many of which are evident in our everyday lives; these systems include power grids, water supply lines and transportation systems. We model the movement of vehicles over highway segments as a system of network flows.

3.1 Notation

We follow the conventions in Ahuja et al. (1993) in defining the following terms. Let $G = (N, A)$ denote a graph where N is the set of nodes, indexed by p (alias q & n), and A is the set of directed arcs (p, q). Let $X_{p,q}$ denote the directed flow along arc $(p, q) \in A$. Let $u_{p,q}$ and $c_{p,q}$ denote the capacity and per-unit cost of flow along $(p, q) \in A$. Let $b(p)$ denote the supply at node $p \in N$ (see Figure 3.1). We use the distance of a road segment as its cost. In our model nodes are equivalent to highway junctions, ZIP code locations, and evacuation locations. Arcs are similarly segments of highway, which connect nodes.

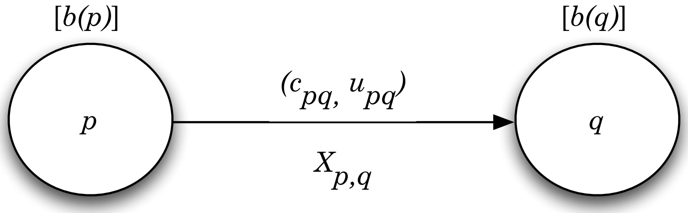


Figure 3.1: Dumbell graph representation illustrating flow from node p to node q.

3.1.1 Point Location Notation

We seek to make the data for our network as clear as possible by prefacing our nodes by the type of node they represent. For example, Zone Improvement Plan (ZIP) code point locations are indicated by starting with a "z" followed by their five-digit number. Highway junctions are indicated by a "p" followed by two or three letters representing the county in which they reside then followed by a three-digit representation of the highway number, immediately followed by the mile-marker. An underscore "_" represents a decimal place for more accurate mile-marker labels. As such ZIP code 95745 is thus "z95745" and a fictional highway junction on I-5 in San Joaquin County located at mile-marker 15.5 is represented by "pSJ00515_5" in situations where no decimal point is required the underscore is omitted. Evacuation points are distinct and do not follow the conventions above, they are: "BayArea," "PointsN," "PointsE," and "PointsS," together they represent the four cardinal directions and are generic to encapsulate all possible evacuation destinations in their general direction. "BayArea" is distinct because all routes of evacuation to the West lead directly to the Bay Area. A complete listing of our point locations can be found in Tables A.1-A.5.

3.2 Building the Network

We follow guidance from CAL EMA Region IV and consider all state and federal highways within Yolo, Sacramento, San Joaquin, and Stanislaus counties. Starting with a collection of road networks extracted in 1990 from the U.S. Census Bureau's Topologically Integrated Geographic Encoding & Referencing system (TIGER) shape files, we updated individual highway segments with data extracted from geographical information software (GIS) shape files provided by California Department of Transportation (CALTRANS). The data for each highway segment includes the distance, the number of lanes, as well as whether the highway is divided. Reconciling the TIGER and the GIS data required considerable effort.

The first step in processing the CALTRANS data was to overlay it on the 20-year-old road data to identify any obvious discrepancies. Figure 3.2 shows some distinct differences between the two data sets. Specifically, some highways are not continuous from their apparent starting point to their terminus. We manually augmented the CALTRANS data to correct these gaps.

Another issue with the CALTRANS data was the representation of highway junctions. For purposes of GIS mapping, it is often sufficient to represent a highway junction by a crossing of individual road segments. However, a network flow problem requires explicit intersections for road junctions (node j in Figure 3.3.B), and we added these manually. After reconciling the data we verified the result by taking a map of the area and then overlaying our constructed network (Figure 3.4).

We then add one node for each evacuation point, selecting it based upon the general direction that the various highways travel. The final evacuation points include one node for the Bay Area in the west, and one node for each of the remaining cardinal directions. We place each on the

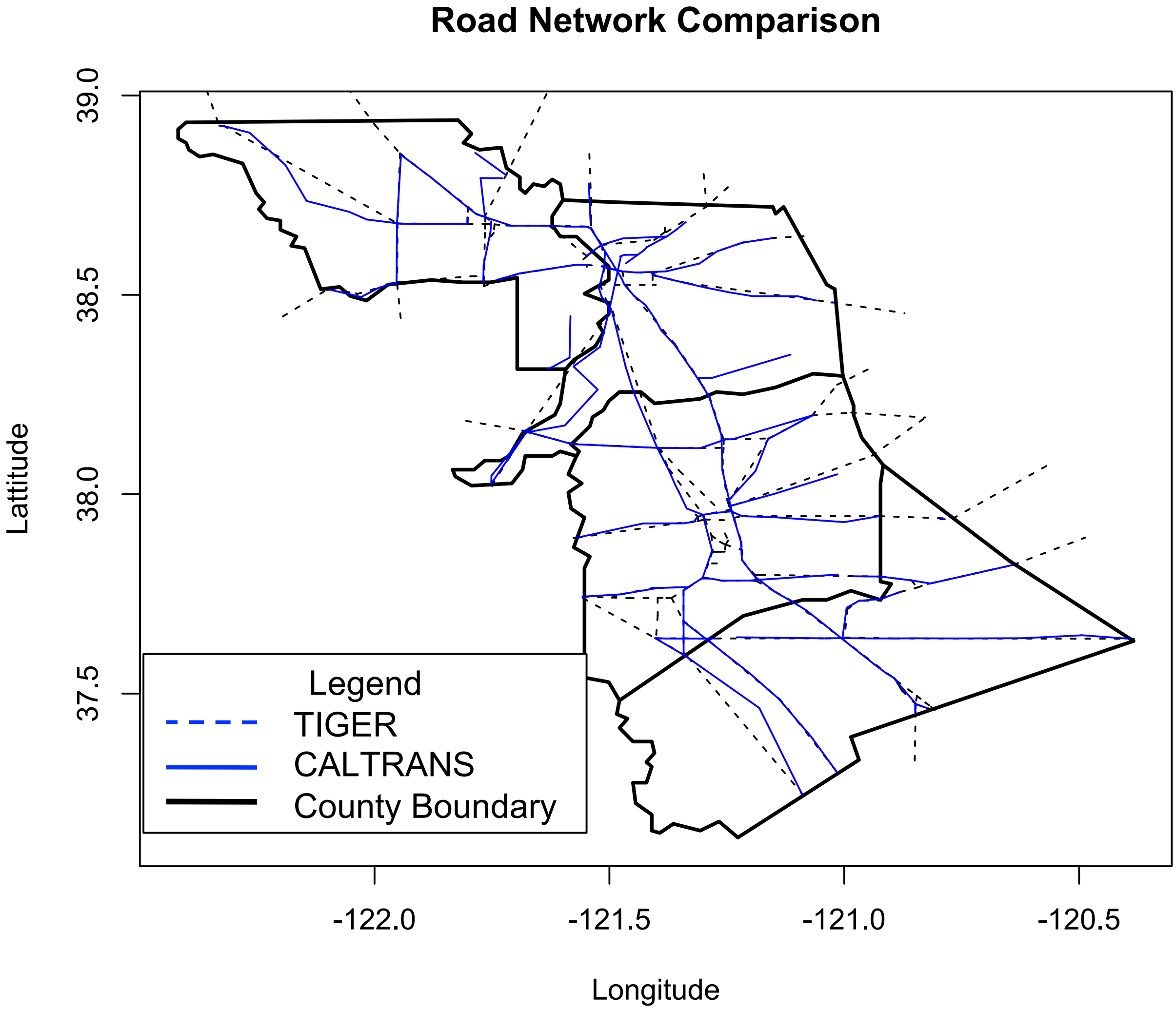
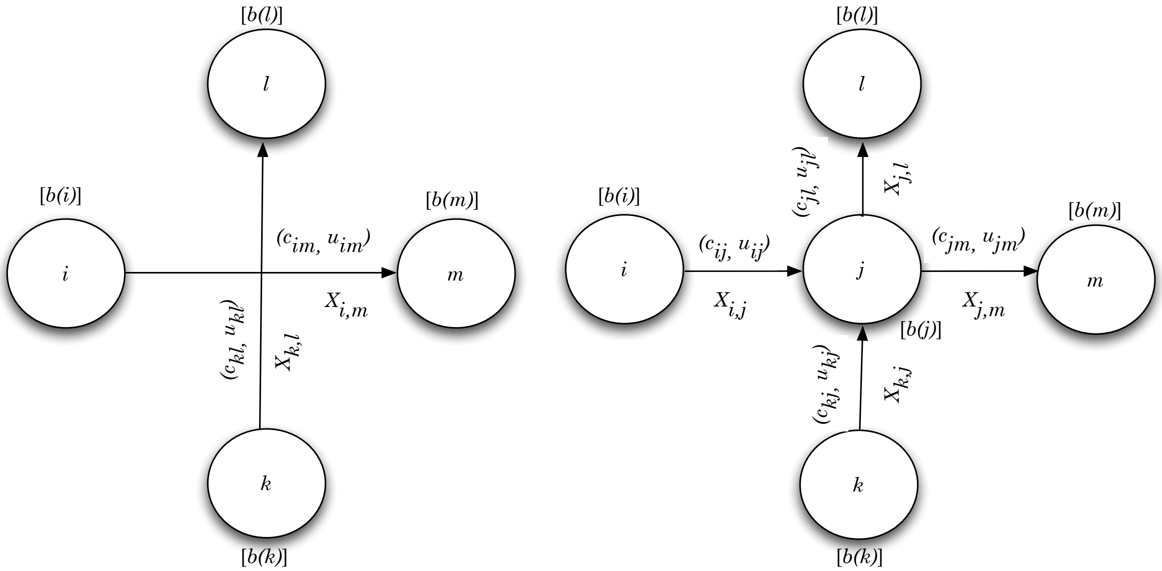


Figure 3.2: State and Federal Highways in Yolo, Sacramento, San Joaquin and Stanislaus counties. Dashed lines are TIGER data set, solid lines are CALTRANS data.

map at a distance far enough from the main highway network so as to be visually obvious, but we do not assign a distance to these notional highway segments. Reaching any of the nodes adjacent to an evacuation point is therefore equivalent to actually evacuating.

The last main input to our model is population data, which we obtain via one of two methods available through the U.S. Census Bureau; five-digit ZIP codes or Census tracks. Census tracks provide a higher level of fidelity than ZIP codes but are not as easily recognized by citizens. ZIP codes encompass larger geographical areas on average but more familiar to civil agencies



A) Crossing arcs without interaction

B) Crossing arcs with interaction

Figure 3.3: Two crossing arcs without interaction (A), junction representation (B)

as well as the population at large. Rather than attempting to draw the geographical region for each ZIP code we use the geographical center of the ZIP code, aka ZIP code centroid, as a supply node (see Figure 3.5). Finally, we connect the ZIP code to the four nearest highway segments (not shown on Figure 3.5). This provides a general representation for a diversity of local access roads and highway on-ramps.

3.3 Model Assumptions

We develop a single commodity network flow model to evaluate the amount of time required for the at-risk populations to evacuate. This is similar to the Rough Cut Capacity Plan model of Ardekani et al. (2006).

1. We assume that the complete schedule of highway inundations (locations and times) is known with certainty in advance.

2. We assume that people evacuate when informed to do so and that highways are devoid of traffic until the evacuation is ordered.

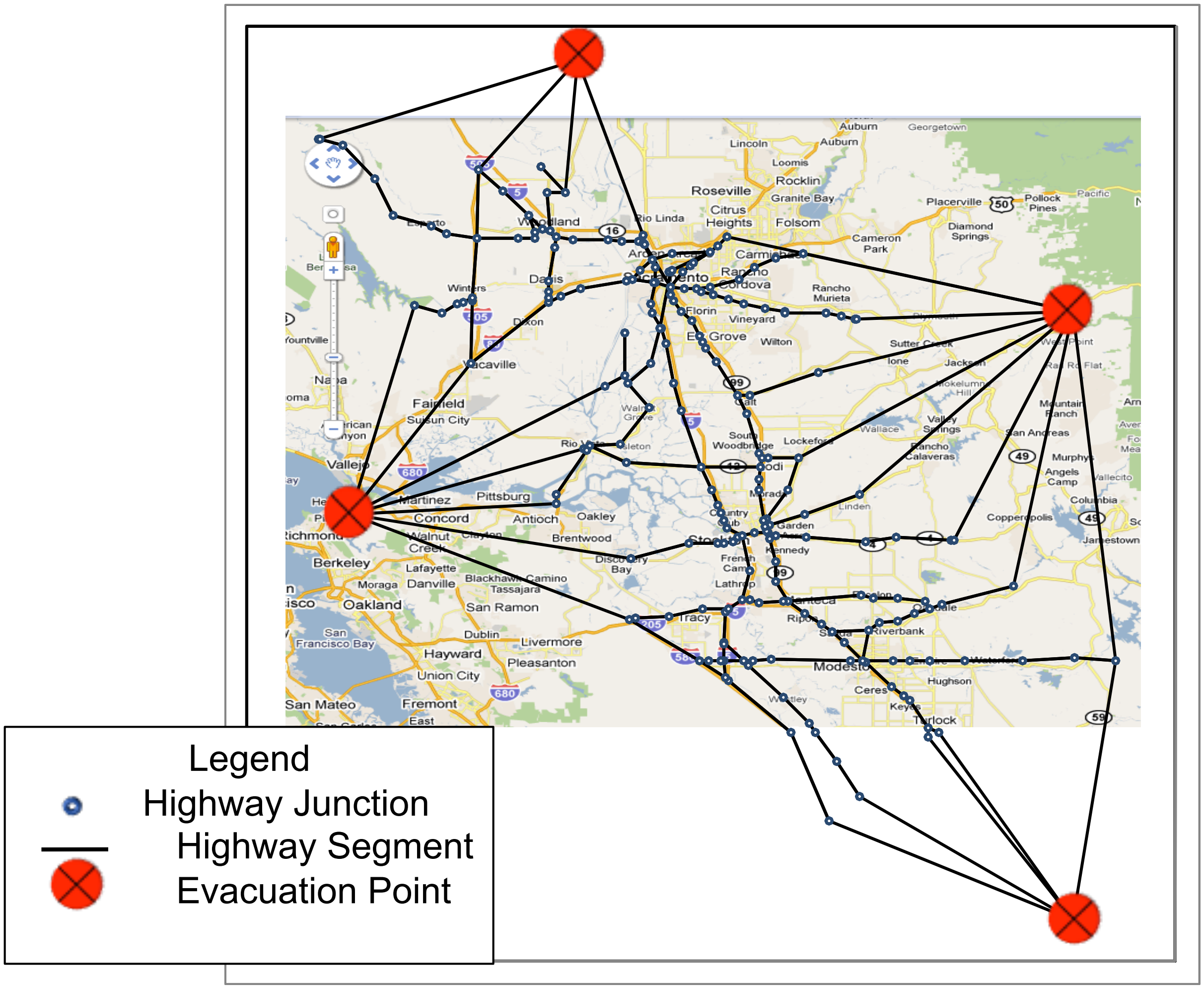


Figure 3.4: Map with constructed network overlaid on the highways in Region IV.

3. We assume that congestion is captured in the capacity of each highway segment in vehicles per hour.

4. We assume that the only thing preventing a population from evacuating is road capacity. If an evacuation route has enough capacity to carry a vehicle during an epoch (three hours for this analysis), then we assume the vehicle has enough time to do so. Furthermore, we assume that the entire populations has access to a vehicle and can evacuate without assistance.

5. We assume that people will evacuate on local highways and not along county roads.

6. We assume people know their neighborhoods well enough to find routes to access the highway. In our model, each ZIP code can access the highway by four separate routes.

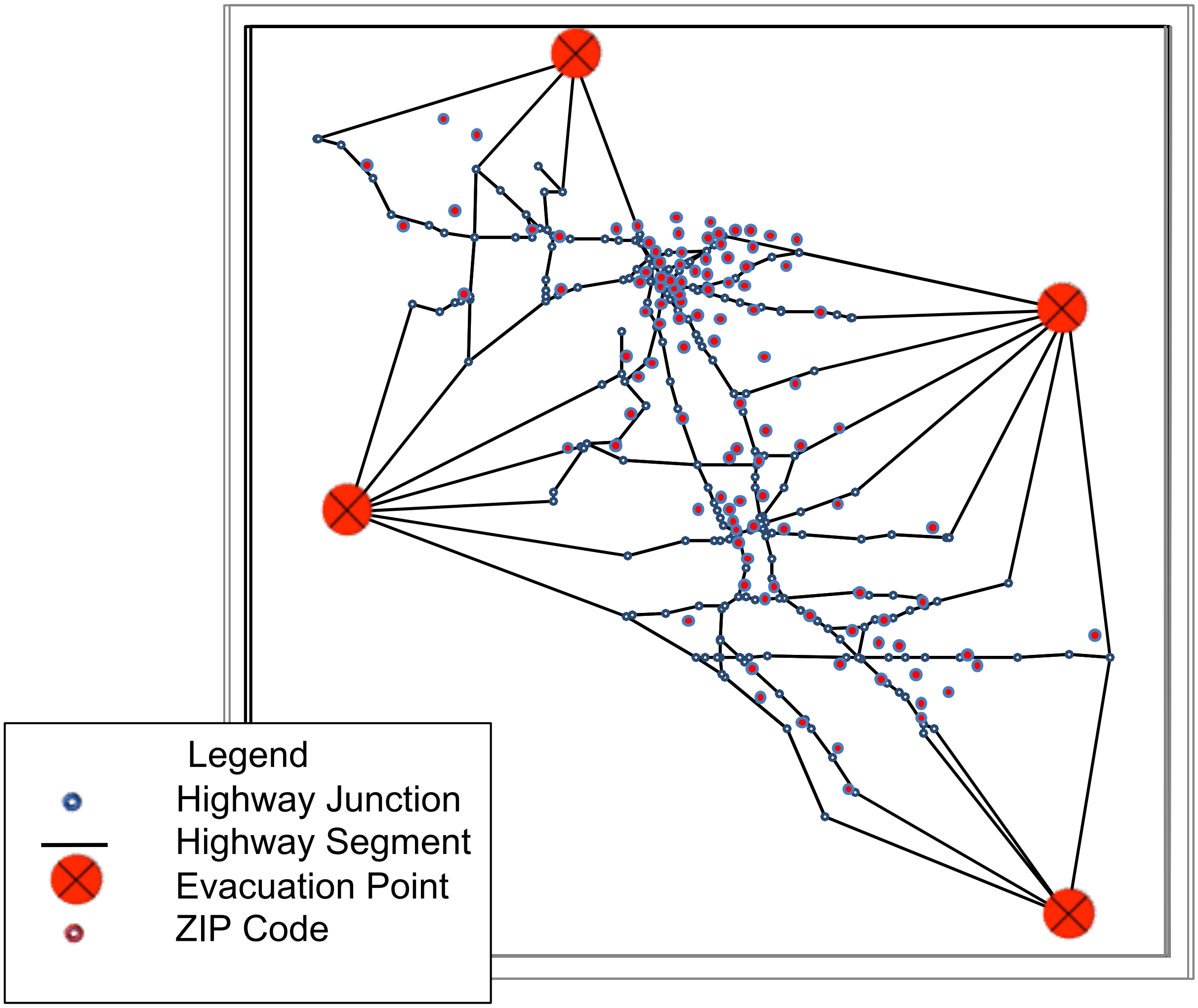


Figure 3.5: Final road network with ZIP codes.

7. We assume that highway on-ramps do not restrict the ultimate evacuation behavior, and we model the capacity of each arc connecting ZIP codes to the highway network with sufficiently high capacity (*i.e.,* 10,000 vehicles/hour) so that they do not cause bottlenecks.

8. We assume that people travel to the evacuation destination that minimizes their time to evacuate.

3.4 Formulation

We present the complete mathematical formulation MINATRISK to solve the single commodity problem.

Index Use [$\sim$ cardinality]

$p \in P$	point location (alias n, q) [$\sim$ 333]
$g \in G \subseteq P$	safe destination point location(s) [$\sim$ 4]
$t \in T$	time epoch (an ordered set), in T [$\sim$ 10 – 20], where t_F is the final epoch
$(p, q) \in A$	set of all arcs (p, q) in A [$\sim$600]
$(p, q, t) \in R$	undirected road segment between p and q in epoch t [$\sim$ 450]
$(p, q, t) \in S$	directed road segment from p to q in epoch t [$\sim$ 250]
	$(p,q) \in S \Longrightarrow \left\{ (p,q) \in R\Big\vert_{p<q} \vee \ \ (q,p) \in R\Big\vert_{p>q} \right\}$

Given Data [units]

$inundation\_schedule_p^t$	a list of highway junctions scheduled to be flooded in epoch $t > 1$
$cap_{p,q}^t$	capacity for evacuee flow during epoch t over directed arc $(p, q) \in S$ [vehicles] (This can be computed as an arbitrary function of exogenous data, or tabulated.)
$dist_{p,q}$	distance from point p to point q [miles]
$evac_p^t$	supply of evacuees from point location p at the start of epoch t [people]
$evac\_pop^t$	total population successfully evacuated in t [people]
$reversible_{p,q}$	indicator of the ability to reverse a segment of highway $\begin{cases} 1, & \text{if arc}(p,q) \text{ is reversible} \\ 0, & \text{otherwise} \end{cases}$
$distlabel_n$	shortest path distance from node n to any safe evacuation point calculated in MINDIST.

Parameters [units]

$pax\_per\_vehicle$	estimated number of passengers per vehicle [people]
$strand\_pen$	penalty incurred for each stranded person in epoch t_F
$ave\_dist^t_{p,q}$	average miles traveled by evacuees [miles/person] $\frac{pax\_per\_vehicle\ dist_{p,q}}{evac\_pop^t}$
$contramiles$	maximum number of contraflow miles authorized in the evacuation [miles]

Decision Variables [units]

$X^t_{p,q}$	directed flow of traffic on arc $(p, q) \in S$ during epoch t [vehicles]
F^t_n	evacuees frustrated at point location n at the end of epoch t [people]
$V_{p,q}$	decision to reverse directed flow capacity on arc $(p, q) \in S$ for all t [binary]

Model MINATRISK

$$Z = \min_{X,F,V} \quad \sum_{t<t_F} \sum_{n \in N} distlabel_n \, F_n^t + \sum_{n \in N} strand\_pen \, F_n^{t_F}$$

$$+ \sum_{t \in T} \sum_{(p,q,t) \in S} ave\_dist_{p,q}^t X_{p,q}^t \tag{3.1}$$

$$s.t. \qquad pax\_per\_vehicle \left(\sum_{(n,q,t) \in S} X_{n,q}^t - \sum_{(p,n,t) \in S} X_{p,n}^t \right) - F_n^{t-1} \Big|_{t>1}$$

$$+ F_n^t = evac_n^t \qquad \forall n \in P, t \in T \tag{3.2}$$

$$X_{p,q}^t \le cap_{p,q}^t (1 - V_{p,q}) + cap_{q,p}^t (V_{q,p}) \qquad \forall (p,q) \in S, t \in T \tag{3.3}$$

$$V_{p,q} + V_{q,p} \le 1 (reversible_{p,q}) \qquad \forall (p,q) \in R \tag{3.4}$$

$$\sum_{(p,q) \in A} dist_{p,q} V_{p,q} + \sum_{(q,p) \in A} dist_{q,p} V_{q,p} \le contramiles \qquad \forall (p,q) \in R \tag{3.5}$$

$$X_{p,q}^t \ge 0 \qquad \forall (p,q) \in S, t \in T \tag{3.6}$$

$$F_n^t \ge 0 \qquad \forall n \in P, t \in T \tag{3.7}$$

$$V_{p,q} \in \{0,1\} \qquad \forall (p,q) \in S, t \in T \tag{3.8}$$

MINATRISK Discussion

This is a single-commodity minimum cost network flow model with periodic state review and time epochs long enough that any person trying to evacuate has enough time within any single epoch to reach any safe destination point, provided sufficient road capacity. The objective function (3.1) minimizes the number of frustrated and stranded evacuees as well as the average distance traveled by evacuees by the end of the evacuation time horizon. Balance of flows constraint (3.2) accounts for flows into and out of a point location during a time epoch. Such flows include persons unable to reach a safe destination point within an epoch, and thus frustrated remain in place until the next epoch. Constraint (3.3) governs directed flow on a road segment that may be influenced by a decision to reverse a normal traffic flow direction. Constraint (3.4) allows at most one direction reversal decision for each road segment. Contraflow constraint (3.5) defines the maximum allowed miles of contraflow which may be used. Stipulations (3.6)–(3.8) define decision variable domains.

3.4.1 MINDIST Shortest Path Model

The flows in formulation MINATRISK are a consequence of the labels *distlabel*$_n$ that "drive" evacuees toward safe locations. We obtain these labels by solving a separate shortest path network problem.

To accomplish this, we create an artificial node $SINK \in N$. We create artificial arcs $(g, SINK) \in A$ with $dist_{g,SINK} = 0, \ \forall g \in G$. We define a new decision variable $Y_{p,q,n}$ to represent the flow originating at $n \in N$ along $(p,q) \in A$. We then solve formulation MINDIST.

Model MINDIST

$$Z = \min_{Y} \quad \sum_{n \in N} \sum_{(p,q) \in A} dist_{p,q} \, Y_{p,q,n} \tag{3.9}$$

$$s.t. \quad \sum_{(p,q) \in A} Y_{p,q,n} - \sum_{(q,p) \in A} Y_{q,p,n} = \begin{cases} 1, & \text{if, } p = n \\ 0, & \text{if, } p \neq \{n, SINK\} \\ -1, & \text{if, } p = SINK \end{cases} \tag{3.10}$$

$$Y_{p,q,n} \geq 0 \qquad \forall (p,q) \in A \tag{3.11}$$

Finally, we set $distlabel_n = \sum_{(p,q) \in A} Y^*_{p,q,n} \quad \forall n \in N$, where Y^* is the set of optimal flows resulting from formulation MINDIST.

3.4.2 Additional Details

In order to perform detailed accounting of flows and generate customized reports we also include the following:

Index Use [$\sim$ **cardinality**]	
$z \in Z$	ZIP code [$\sim$ 110]
$z(p)$	ZIP code of point location p [$\sim$ 110]
$e \in E \subseteq P$	dynamic set of evacuated locations [$\sim$ 50 – 100]

$c \in C$	county [$\sim$ 5]

<u>Given Data</u> [units]

lat_p, lon_p	coordinates of point location [degrees]
pop_p	population of point location p [people]

With these, we can produce reports that, for example, keep track of the movement of evacuees county-by-county per time period. This kind of information is particularly useful for emergency planners at the county-level who setup Evacuation Control and Assistance Points (ECAPs) that provide food, water, and vehicular assistance to evacuees.

THIS PAGE INTENTIONALLY LEFT BLANK

CHAPTER 4:
Analysis

CAL EMA Region IV has many possible evacuation scenarios, however we narrow our focus to a specific few to illustrate key features of the region and our model. We first establish a "base case" and then apply our models to analyze differences in the evacuation behavior for each scenario.

4.1 Establishing the Base Case

To understand how the highway network reacts under various what-if scenarios, we first define a base case and evaluate it under two different scenarios. The *base case* considers evacuation where no contraflow is utilized. This is commensurate with current California Highway Patrol's (CHP) Standard Operating Procedures (SOP). We also assume that no highway segments are closed due to flooding or accident. This base case allows us to analyze the optimal performance under current SOP. We apply this case to two specific scenarios. The first scenario is a situation in which all ZIP codes within Sacramento County must evacuate, we refer to this scenario as the Sacramento County scenario, or simply as *Sacramento County*. In the second, we apply the base case to a scenario where all ZIP codes along rivers within the four counties must evacuate, we refer to this scenario as the River-Side scenario or simply as *River-Side*.

4.2 SCENARIO: Sacramento County

As stated previously, this scenario forces the evacuation of all ZIP codes within Sacramento County. We select this scenario because Sacramento County is the most densely populated county of the four considered, with approximately 1,182,491 residents (U.S. Census Bureau, 2000). The evacuation of this many people will quickly saturate the highway network and allow us to analyze how it performs under high-demand situations. We then manipulate the parameters of the model to generate changes to the scenario.

4.2.1 Run Profiles

We manipulate parameters to influence the evacuation results from our model. For each run of the model we vary the number of passengers per vehicle ($pax\_per\_vehicle$) also referred to as PPV, from PPV=1 to PPV=4 incrementing by half a passenger with each iteration. Additionally, we change the maximum number of authorized contraflow miles ($contramiles$), or CFM, from

CFM=200 down to CFM=0 reducing it by 50 with each iteration. By doing this we are able to analyze the effect these parameters have on each scenario. We start with the base case applied to each of the two scenarios and then constrain them, this results in the following profiles:

1. Base cases for both scenarios
2. Loss of the ability to evacuate to PointsE
3. Loss of the ability to evacuate to BayArea
4. Highway I-5 inundated at San Joaquin mile-markers 15, 20 and the CA-120/I-5 interchange
5. Highway CA-99 inundated at San Joaquin mile-markers 6, 9, and the CA-120/CA-99 interchange
6. Both highways I-5 and CA-99 inundated at the mile-markers listed above
7. Highway I-5 inundated as before with the addition of losing the ability to evacuate to PointsE

These combinations result in 490 distinct evacuation scenarios.

4.2.2 Results

We formulate our model MINATRISK using General Algebraic Modeling System aka GAMS (GAMS, 2010) and solve each evacuation scenario to within 0.1% of optimality using CPLEX 12.02 (ILOG, 2007) on a personal computer with an Intel Xeon CPU at 3.16 GHz. The computation time to solve each scenario depends on the model parameters, including the road closures, if any, the number of passengers per vehicle, and total contraflow miles; resulting in a range of five seconds for an individual scenario to 41 minutes with 35 scenarios solved in a single run.

Table 4.1 is a partial listing of results from a single run of the model. It lists PPV and CFM at the top and reports arrivals of evacuees by epoch to each one of the evacuation points, followed by the number of stranded people still waiting to evacuate at the end of the epoch. It reports if anyone is stranded, how many miles of contraflow were used and finally reports the cumulative number of evacuees at each evacuation point in every time period. We also produce county-wise reports, provide distance information and measure highway segment utility which is used for graphing the evacuation over time.

Table 4.1: Example of output for evac_sp_tot.csv. The last column indicates the table continues to the right, one column per additional epoch.

pax_per_vehicle=	1	contramiles=	200	
Evacuations by time period				
	$t1$	$t2$	$t3$	$t4 \cdots$
BayArea	45000	42231	42000	$\cdots$
PointsN	30000	30000	30000	$\cdots$
PointsE	48000	48000	48000	$\cdots$
PointsS	18000	18000	18000	$\cdots$
Frustrated	1041491	903260	765260	$\cdots$
Stranded	0	0	0	$\cdots$
Contraflow miles	135.8	135.8	135.8	$\cdots$
Cumulative evacuations by time period				
BayArea	45000	87231	129231	$\cdots$
PointsN	30000	60000	90000	$\cdots$
PointsE	48000	96000	144000	$\cdots$
PointsS	18000	36000	54000	$\cdots$

Using the data from Tables A.6–A.9 in the Appendix we generate Figure 4.1. Figure 4.1 depicts the rate that evacuees reach exit points. From this figure we can see that people evacuate in the shortest amount of time when they travel together. In Figure 4.1, we observe that the PPV=4 case evacuates fastest, which is to be expected, while the PPV=1 case takes evacuees more than three times as long to evacuate.

Assumptions about the number of passengers per vehicle

We observe this trend consistently over multiple scenarios and therefore conclude that the number of passengers traveling in an evacuating vehicle can greatly influence evacuation times. The average family size in Sacramento is 2.57 people (U.S. Census Bureau, 2000). In the remaining analysis, we assume people will travel with other evacuees but will at times be greedy and take more than one vehicle. We conservatively assume PPV=2 anytime we discuss evacuation rates and times unless specifically mentioned otherwise.

Based on the results above, an evacuation of Sacramento County, assuming CHP's SOP and barring any highway interruptions, will take an estimated 21 hours for all evacuees to reach an evacuation point. This is a best case scenario: evacuees behave according to a central planner (our model) who tells them exactly where and when to go so that the overall evacuation is optimized. Table 4.2 presents the details for the number and percentage of people reaching

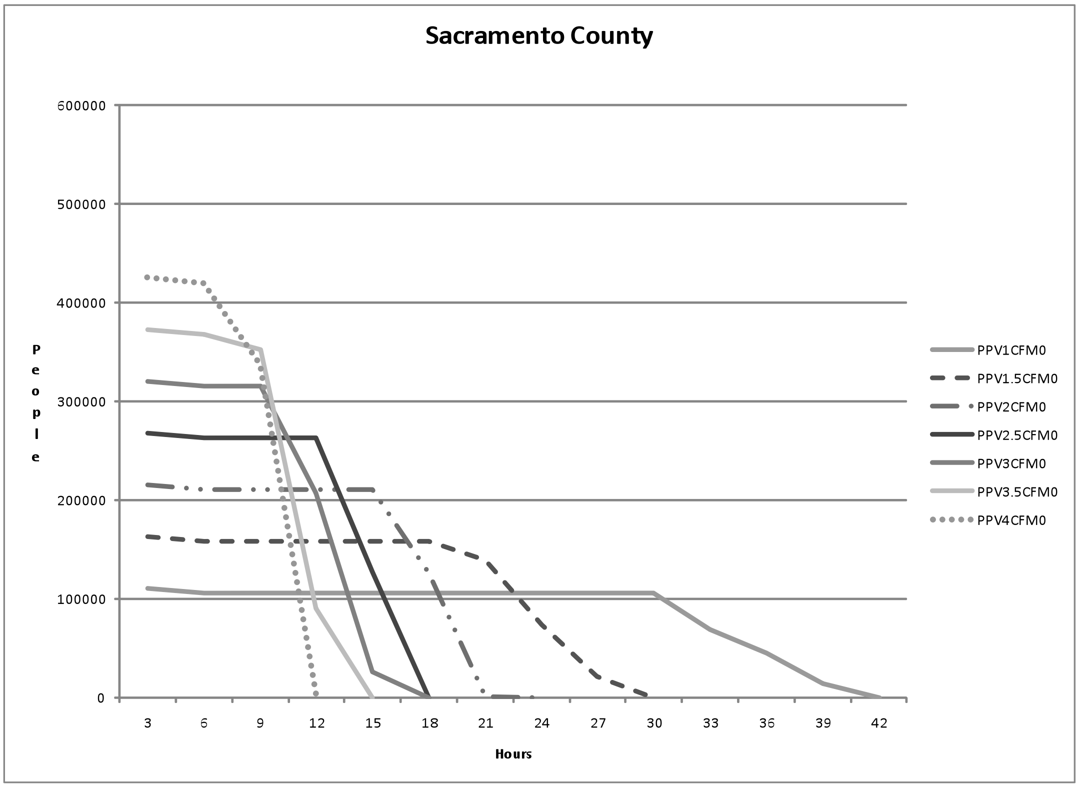


Figure 4.1: With no contraflow available to increase the rate that people depart, the importance of carpooling becomes clear. The legend notation depicts the number of passengers per vehicle followed by the number of contraflow miles used.

the various evacuation points. From this table we observe that 23% of the population travels North, 33% to the Bay Area, 44% to the East and 0% travel South. To understand why evacuees do not travel South recall that our objective function (3.1) minimizes the number of stranded and frustrated people in the network as well as minimizes the average distance evacuees travel. This means, for example, that evacuees traveling South along I-5 will fill I-5 to capacity in Sacramento County but turn off I-5 onto another highway to minimize the distance they travel to evacuate from the region. They will find and take the shortest path to the closest evacuation point. In Figure 4.2 we observe that the southern portion of the regions highways are not utilized by evacuees. If our objective function were adjusted to give preference to major highways over state highways, the flow patterns would change, but the basic results would not.

4.2.3 Considering Contraflow

Having established a baseline, we consider the use of contraflow. Figure 4.3 depicts evacuation clearing times for PPV combinations and depicts a range from CFM=0 to CFM=200. From this figure we see that there is no benefit to the use of contraflow when PPV=4. The greatest benefit

Table 4.2: Summary of evacuation results by evacuation point (in percentage and population) assuming PPV=2 and CFM=0. In these scenarios all evacuees were able to evacuate.

Case	PointsN	PointsS	BayArea	PointsE
Sacramento County	23%	0%	33%	44%
	276,000 people	0 people	389,413 people	517,078 people
Loss of PointsE	37%	8%	55%	0%
	432,000 people	98,004 people	652,487 people	0 people
Loss of PointsE & I-5	39%	13%	48%	0%
	462,000 people	158,004 people	561,231 people	0 people
Loss of BayArea	32%	15%	0%	53%
	384,000 people	175,797 people	0 people	622,694 people
Loss of I-5	23%	4%	27%	46%
	276,000 people	48,000 people	317,413 people	541,078 people
CA-99	23%	0%	33%	44%
	27,000 people	0 people	395,413 people	517,078 people
Loss of CA-99 & I-5	24%	0%	28%	48%
	288,000 people	0 people	332,312 people	562,179 people
River-Side Evacuation	18%	21%	25%	36%
	210,000 people	233,232 people	283,402 people	408,000 people
Loss of PointsE	29%	31%	40%	0%
	324,000 people	351,207 people	459,427 people	0 people
Loss of PointsE & I-5	33%	24%	43%	0%
	378,000 people	274,326 people	482,308 people	0 people
Loss of Bay Area	28%	24%	0%	48%
	324,000 people	351,207 people	0 people	459,427 people
Loss of I-5	19%	17%	27%	37%
	216,000 people	195,207 people	298,688 people	424,739 people
Loss of CA-99	18%	21%	25%	36%
	199,119 people	243,207 people	278,308 people	414,000 people
Loss of CA-99 & I-5	19%	17%	27%	37%
	216,000 people	195,207 people	298,688 people	424,739 people

of contraflow comes in the case of PPV=1, and this reduces clearing times by nine hours. This benefit drops to six hours as PPV increases by an additional half passenger, and decreases to three hours when PPV averages 2.5, ultimately dropping to zero benefit at PPV=4.

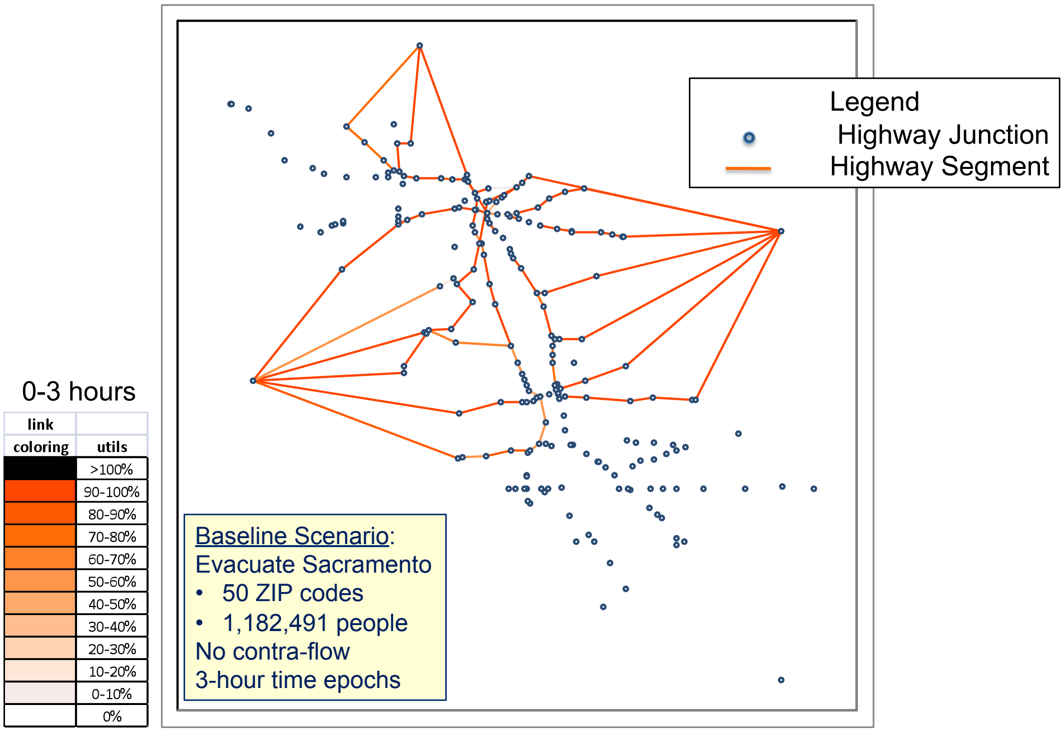


Figure 4.2: This depicts the capacity utilization of the various highways in the region as Sacramento County evacuees depart the region in the first epoch.

4.2.4 An Imperfect Evacuation

The previously described scenario describes a perfect evacuation. Reality tells us to stress the evacuation in more realistic ways. Consequently, we run several "what-if" scenarios as described above. We next envision a scenario in which evacuees cannot evacuate to either PointsE or BayArea.

Loss of PointsE

We imagine a situation where rain and melting snow cause a deluge of runoff from the mountain region. This runoff washes out roads and causes mud-slides. Snow at higher elevations makes high-mountain passes impassible and thus evacuation to PointsE no longer possible. Figure 4.4 shows the resulting rate of evacuees arriving at other evacuation points when they cannot go east. Table 4.2 illustrates the changes in the evacuation; 156,000 additional people evacuate to PointsN, 98,000 extra evacuees travel to PointsS, and an additional 263,000 drive to BayArea.

We again consider the potential benefit of using contraflow. Figure 4.5 shows that contraflow helps in the situation where evacuees average PPV=1 and this decreases clearing times by six hours with the use of CFM$\geq$150. Interestingly, we also observe that the use of CFM=50 *in-*

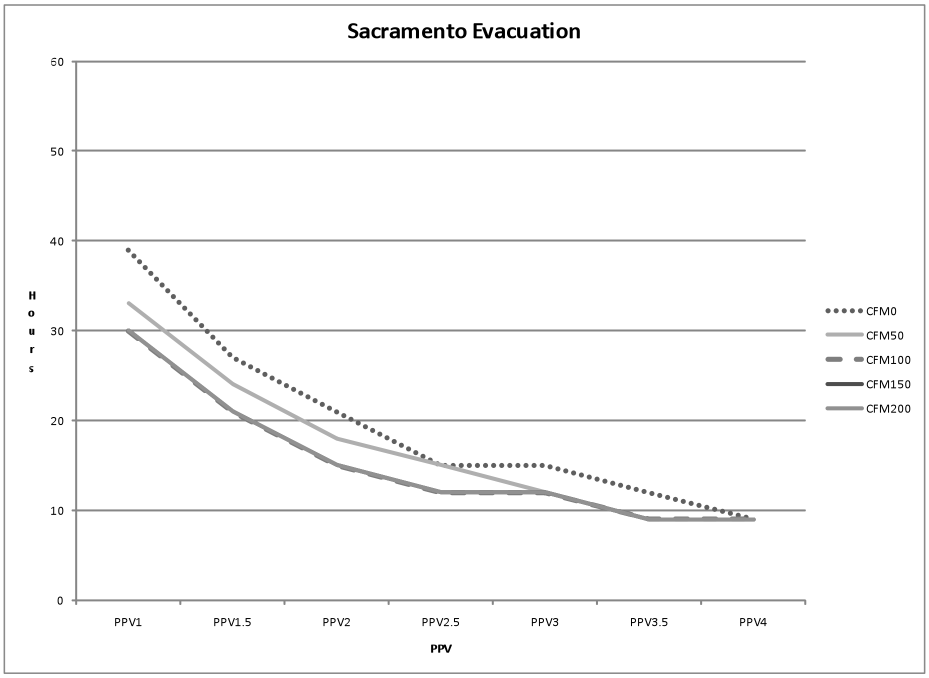


Figure 4.3: Evacuation clearing times comparing the use of contraflow combinations with various passenger combinations. The greatest benefit of contraflow comes when evacuees are one to a vehicle. As PPV increases the benefit of contraflow decreases.

creases clearing times from 54 hours to 60 hours with contraflow established on a small segment of CA-99, north of Sacramento. In this case, our model chooses to use contraflow to push additional vehicles to the edge of the highway network. But, because the capacity of the road segment inbound to the evacuation point is small it then takes several additional time periods for these evacuees to reach safety. The net savings in the cost of frustrated passengers outweighs the cost of additional time periods. This type of trade-off is inherent to our cost-based formulation, and while it sometimes produces results that seem unnatural they are mathematically correct.

Loss of BayArea

We also analyze loss of the ability to evacuate people west to the San Francisco Bay Area. Much concern about flooding in the region revolves around the levee system and the risk of their failure during a major earthquake. The geologic faults which run through this portion of the Central Valley of California have not shifted in over 11,000 years (California Department of Conservation, 2011). Assuming the earthquake does not originate from one of these old faults, then it would likely come from one of the faults that run through the Bay Area. To cause such extensive damage this earthquake would need to be of such an amazing magnitude that the Bay Area would almost certainly have evacuation issues of its own, thus making evacuations from

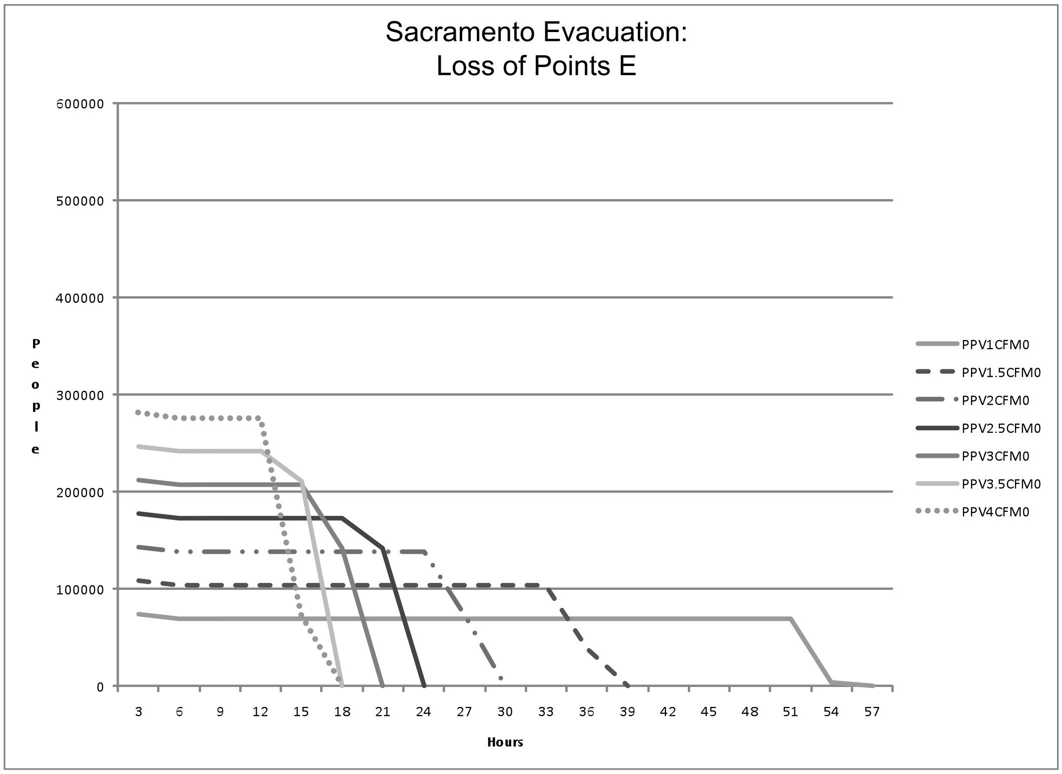


Figure 4.4: The rate that evacuees reach available evacuation points drops by over 100,000 people/hour if PointsE are lost as an evacuation location. Evacuation times increase six hours as a result for PPV=2, 18 hours for PPV=1.

the Central Valley impossible.

The impact caused by losing the ability to evacuate to BayArea is not as great as the loss of PointsE (see Figure 4.6) and does not increase evacuation times. From Table 4.2 we determine that of the 33% of people who evacuated to BayArea in the base case, 9% travel to PointsN, 15% to PointsS and an additional 9% to PointsE. Of the many cases we examine, the loss of BayArea results in the largest number of people traveling to PointsS (175,800 people) and to PointsE (622,700 people).

We observe that contraflow is most beneficial for the case of PPV=1 with clearing times eased by six hours, but the benefit is only three hours when PPV=1.5 (see Figure 4.7).

Highway Inundations

Note that $inundation\_schedule_p^t$ in our model defines a schedule of inundated point locations, *e.g.*, $inundation\_schedule_p^t = pop_p, \forall(p,t) \in inundated_p^t$. We assume that each point location in $inundated_p^t$ will be inundated at most once, and that in time epochs following such an inundation, all road segments incident to an inundated point location would be lost. That is to

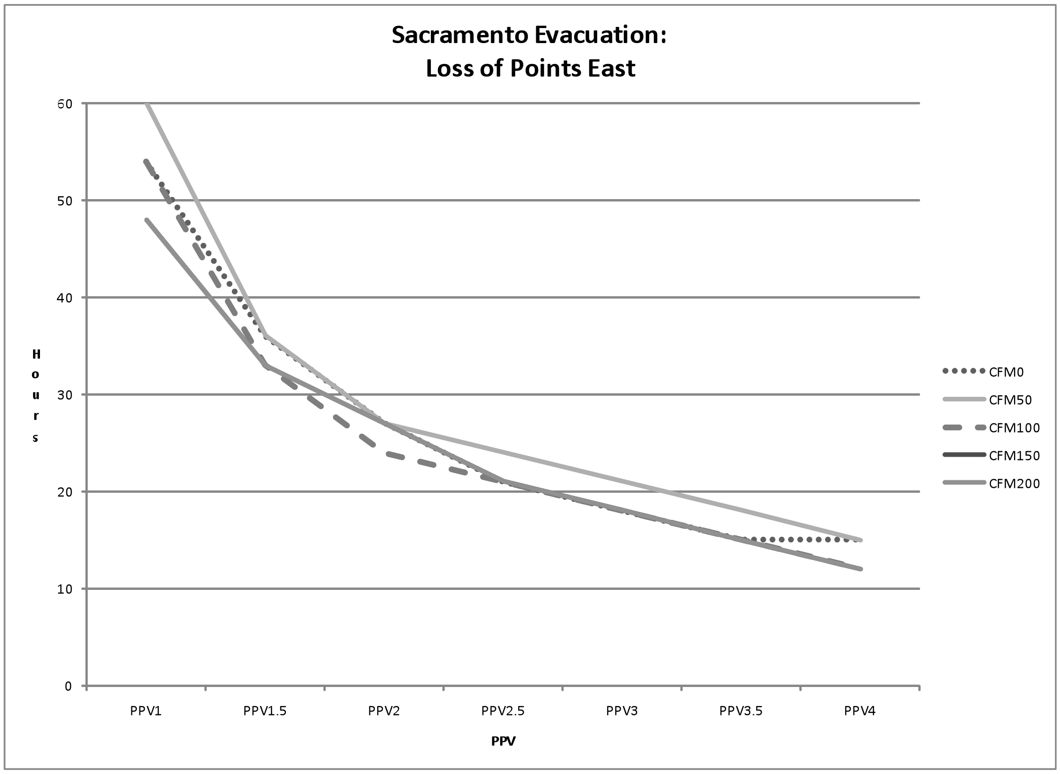


Figure 4.5: The optimal use of contraflow can hinder evacuations. Here CFM=50 causes an increase in clearing times in the PPV=1 scenario. Again, contraflow provides the greatest assistance to clearance times in the PPV=1 scenario with the use of CFM=200.

say, $inundation\_schedule_p^t > 0 \Longrightarrow cap_{p,q}^{\tau} = cap_{q,p}^{\tau} = 0, \forall \tau > t.$

We select highway segments from I-5 and CA-99 in such as manner as to create a cut-set when used together. This cut-set has the impact of preventing any flow from traveling to PointsS from any points north of the cut, and is similar to highway closures experienced in the flood of 1997. Table A.11 provides a specific listing of which highway segments were inundated during which epoch.

As one might expect, we find that the Sacramento County evacuation does not differ in a significant way from the base case scenario when the highway inundations are much further south than the evacuating populations (see Table 4.2).

During a hypothetical inundation of I-5 and the loss of PointsE, we observe that many evacuees access BayArea through routes off I-5. Further, the combination of the loss of I-5 and PointsE drive evacuating populations to take different routes (see Figures 4.8 & 4.9). Despite these obstacles, when we compare this evacuation to the case where PointsE is lost, we find the

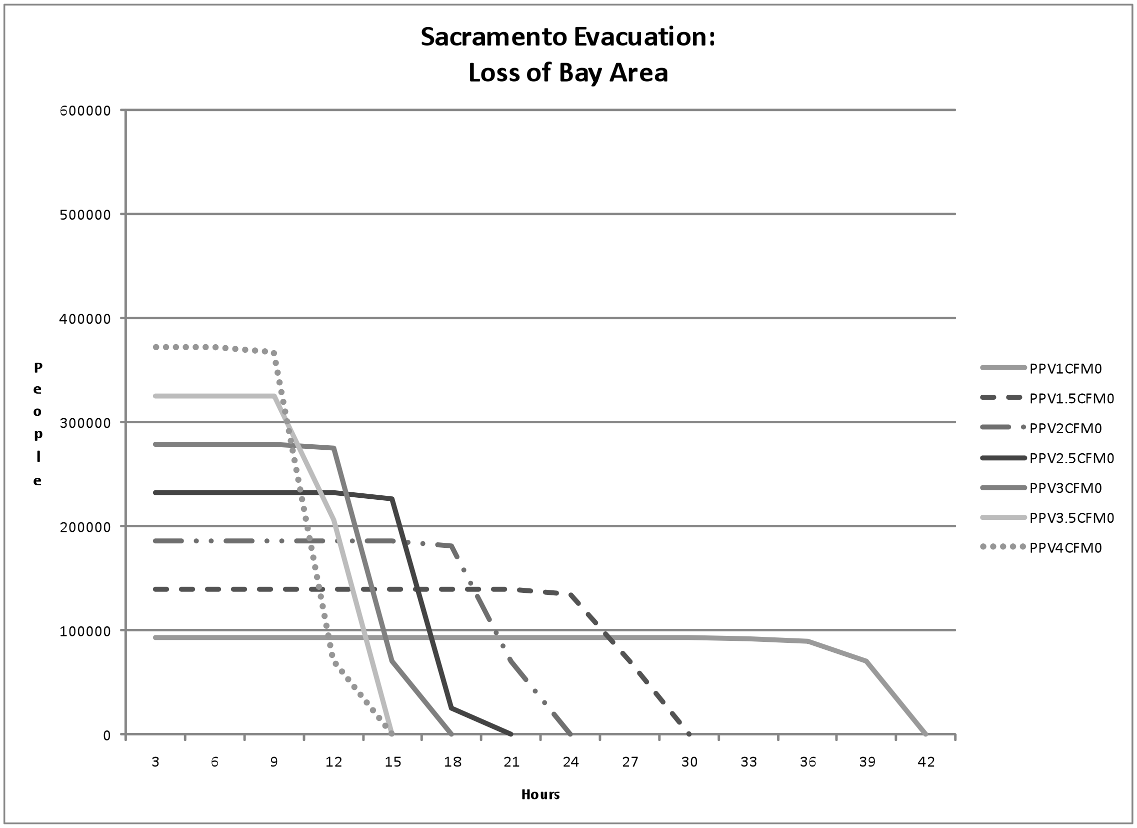


Figure 4.6: Here we observe that the rates of evacuees in the PPV=4 case evacuates almost 100,000 more people per epoch than the loss of PointsE scenario, but rates remain below the evacuation rate of the base case.

difference in populations at the evacuation points are; 2% more evacuate to PointsN (creating the largest demand at PointsN of all our scenarios), 5% more go South, 7% fewer people travel to BayArea.

4.3 SCENARIO: River-Side Evacuation

Given the history of flooding in the region presented in Chapter 1, we model an evacuation scenario more commensurate with historical precedence. Very special circumstances would be required to force all of Sacramento County to evacuate while the other counties nearby remain unaffected. Therefore, we select a set of ZIP codes which border major rivers within the region, and name this set of ZIP codes "River-Side". As demonstrated in the 1997 floods, communities closest to rivers are usually impacted to the greatest degree when levees fail or are crested. With this scenario we analyze the impact on the highway network of an evacuation of similar size to Sacramento County (50 ZIP codes with approximately 1,134,634 million residents (U.S. Census Bureau, 2000)) but spread over a larger area.

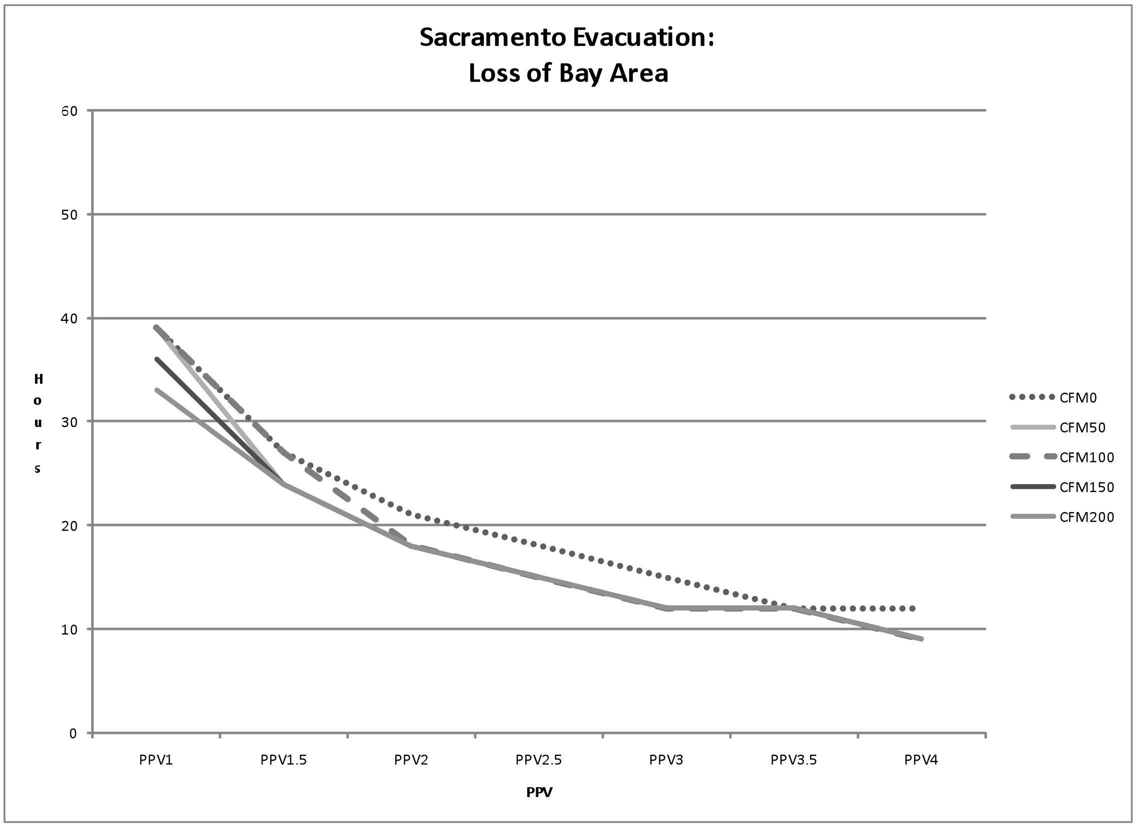


Figure 4.7: Again the addition of contraflow provides only a three hour improvement on evacuation times in the PPV=2 case.

4.3.1 Run Profiles

As with Sacramento County, we run all the same scenarios on the River-Side case. This allows us to compare the effects of evacuating a highly populated region with an evacuation where the population is spread over a greater area.

4.3.2 Results

The River-Side evacuation scenario results in faster evacuation than the Sacramento County scenario (see Tables A.8 & A.9). Further, we observe that evacuees are more evenly distributed across the possible evacuation locations with 18% arriving to PointsN, 21% to PointsS, 25% to BayArea, and 36% to PointsE. In the case of PPV=2 and CFM=0, evacuees evacuate nine hours earlier than the Sacramento County case, in as few as 12 hours versus 21 hours (see Figure 4.10). This is to be expected, as each evacuation node has a significant number of evacuees that begin their evacuation in close proximity.

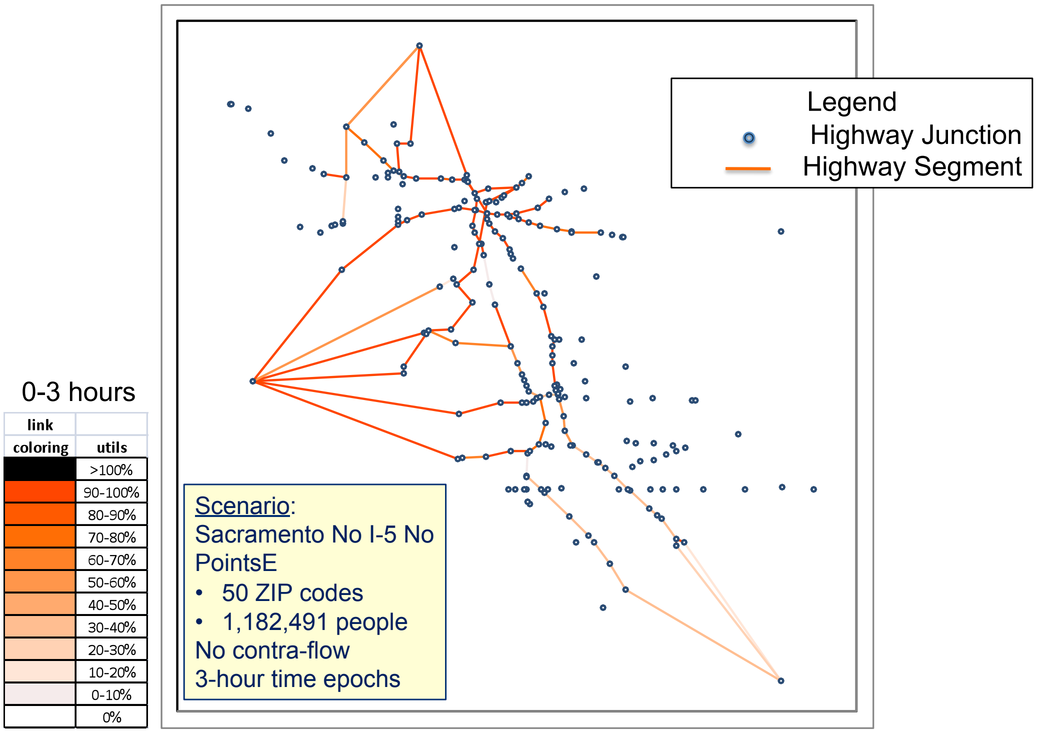


Figure 4.8: Sacramento County evacuees flow through the highway network with the loss of PointsE in epoch one prior to the inundation of I-5.

4.3.3 Considering Contraflow

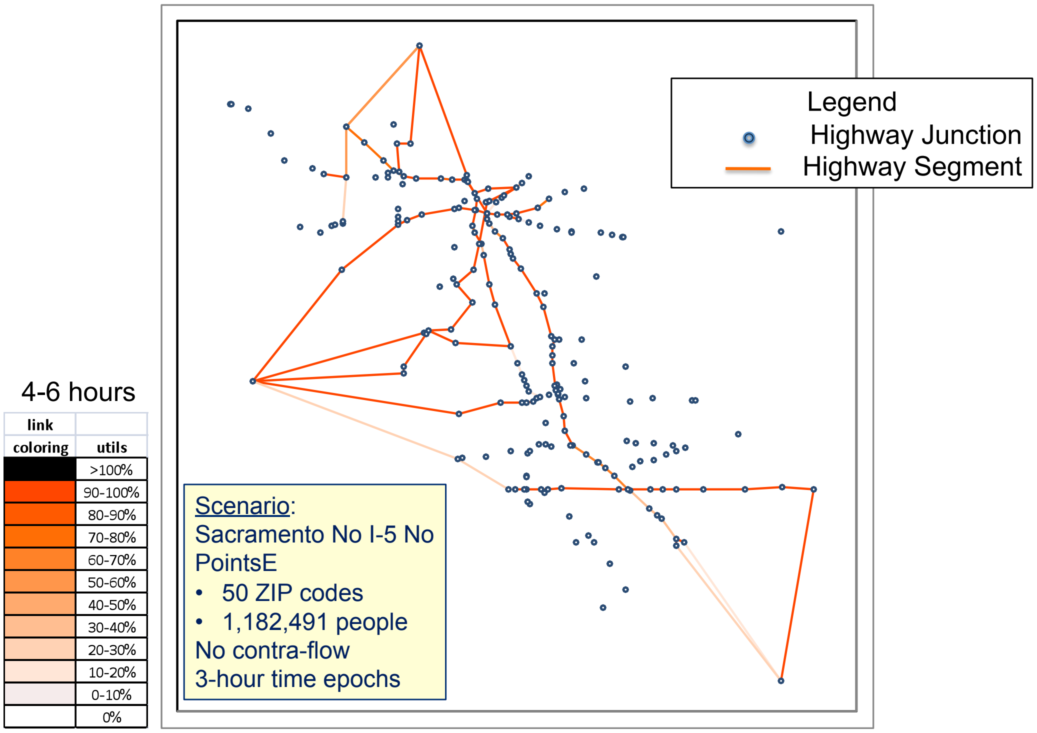
After the mediocre improvements contraflow provided in the Sacramento County case, we again evaluate contraflow to see if it assists evacuees departing the area. Figure 4.11 portrays a more restricted view of contraflow than observed in the Sacramento County evacuation. At PPV=1, where one would expect to see the greatest impact, contraflow does not provide any relief, indicating the greatest easing of clearing times results from an increase in PPV.

4.3.4 An Imperfect Evacuation

We submit the base case River-Side evacuation to several "what-if" scenarios to understand how the evacuation will progress under stress.

Loss of PointsE

As before the loss of PointsE greatly impacts the rate at which evacuees reach safety and increase clearing times for PPV=2 by six hours (see Figure 4.12).



Scenario:
Sacramento No I-5 No PointsE

- 50 ZIP codes
- 1,182,491 people

No contra-flow
3-hour time epochs

Figure 4.9: Sacramento County evacuees detour around inundated highways and most of those detoured evacuate South.

Loss of BayArea

While losing the ability to evacuate to the Bay Area does increase the amount of time to evacuate the population, the network is able to evacuate 50,000 more evacuees per epoch than the PointsE scenario.

Highway Inundations

We systematically inundate the same highways as before in the second epoch. We find that because of the distributed nature of the evacuation locations these highway inundation schedules have a minimal impact on evacuation efforts. At most only 4% or 45,000 people of the overall population are affected.

However, in the situation where I-5 is inundated and PointsE is lost, the evacuation forces people to evacuate North and West to the Bay Area. As compared to the scenario where PointsE was unavailable as an evacuation location this evacuation results in 4% more people traveling to PointsN, 7% fewer traveling to PointsS, and 3% more to BayArea.

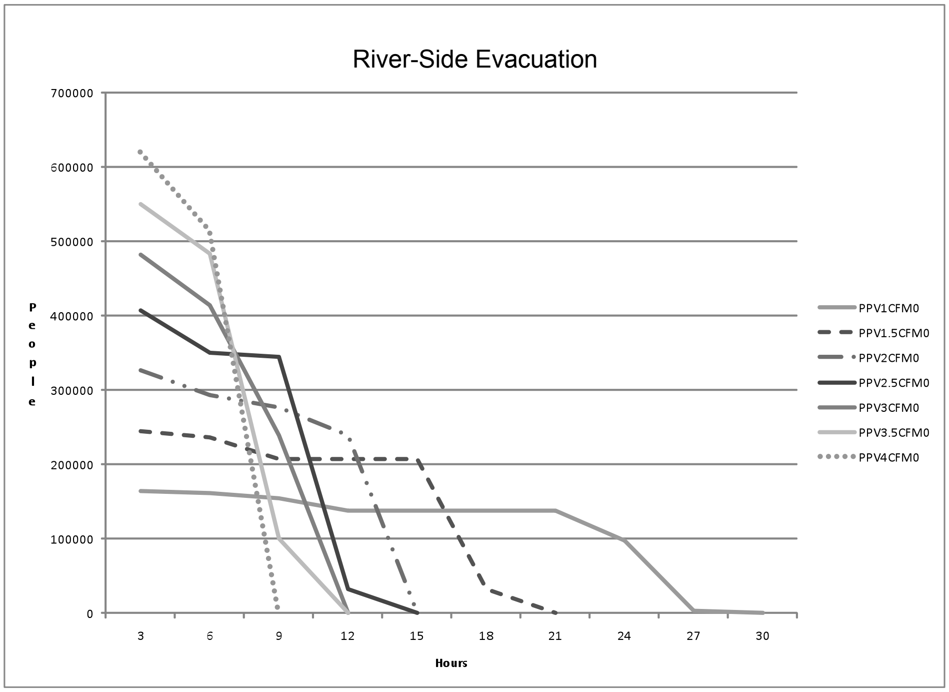


Figure 4.10: Evacuation rates for the River-Side evacuation show an amazing increase in the number of people able to evacuate per epoch. PPV=2 increases by 100,000 people per epoch compared to the Sacramento County evacuation.

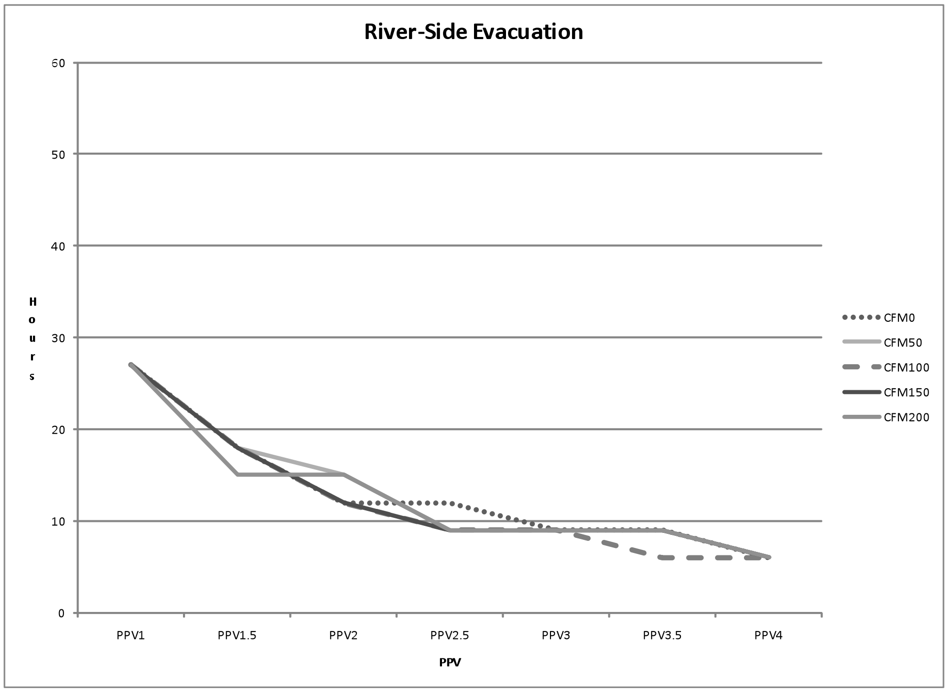


Figure 4.11: Contraflow results for the River-Side base case evacuation. This graph shows that contraflow only helps in some scenarios and only eases clearing times by three hours.

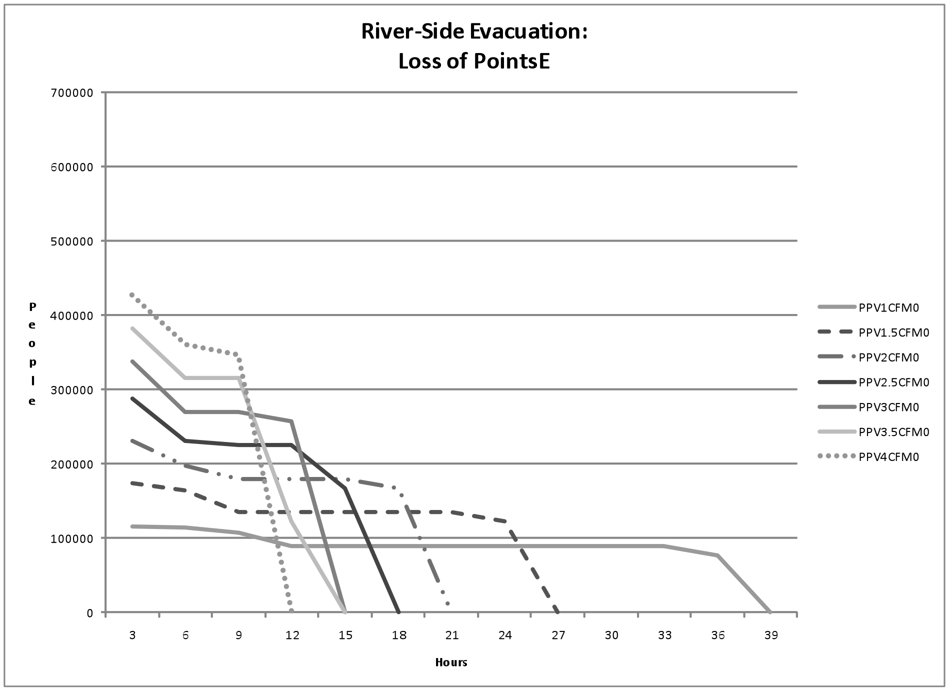


Figure 4.12: Evacuation rates for PPV=2 decrease by 100,000 people per epoch compared to the base case and increase clearing times by six hours.

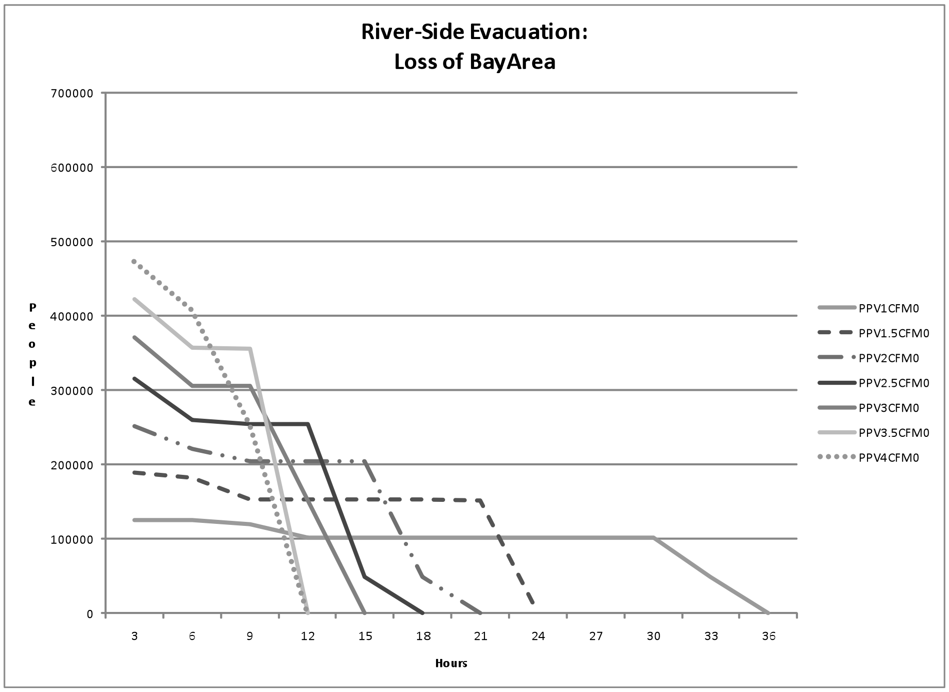


Figure 4.13: Evacuation rates for PPV=2 decrease by 50,000 people per epoch compared to the base case and increase clearing times by six hours.

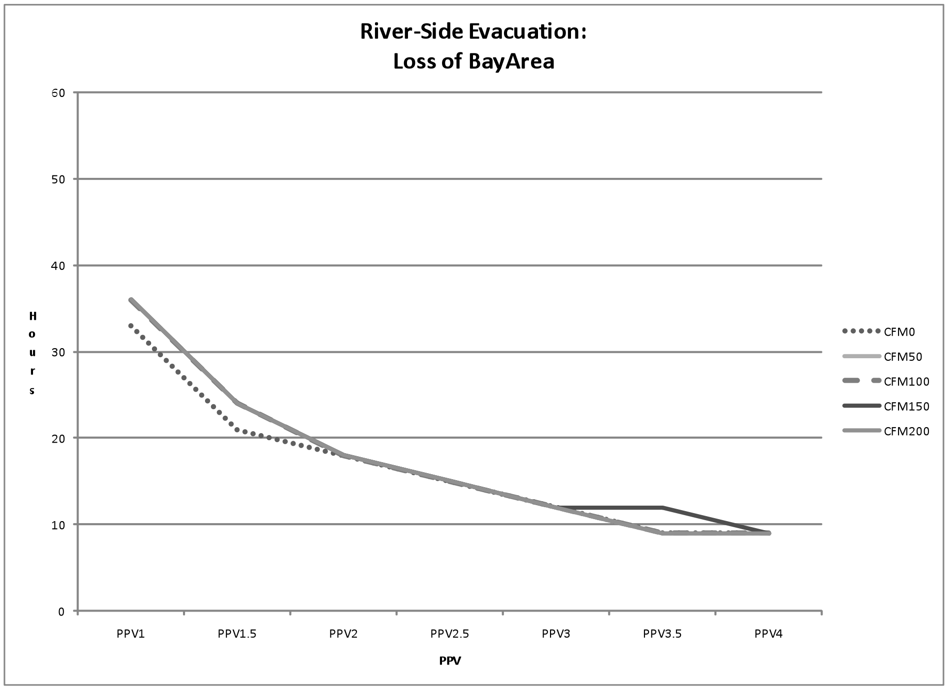


Figure 4.14: Contraflow does not significantly improve River-Side evacuation clearing times in the event of the Bay Area being cut off to evacuees.

4.4 Is Contraflow Worth the Effort?

Undeniably, Emergency Services would face a daunting challenge to set up contraflow in a region not pre designed for it. It would require teams at every on-ramp and off-ramp to direct traffic in the appropriate direction. But the ultimate question remains, is the amount of effort required to force a contraflow plan worth the increased clearing times of evacuees?

4.4.1 What We Expected

As modelers, we fully expected that contraflow would provide significant help to evacuees in reaching evacuation points since it represents a “relaxation” of the capacity limits on segments that have contraflow established. In some instances, contraflow did improve clearing times specifically where more densely populated areas were required to evacuate. But, the results were not as dramatic as we expected. Given the greatest benefit in clearing times is three to six hours and only in instances where PPV=1, we therefore conclude that the level of effort to set-up the contraflow should be spent elsewhere. With that said, we believe that preplanning of evacuation routes warrants further evaluation for the area since the region has so many possible routes that evacuees may take. It is important to route evacuees through areas with bottlenecks as effectively as possible to minimize evacuation times. This will allow for more effective pre-staging of relief supplies.

4.4.2 Analysis and Verification

In order to validate our findings that contraflow provides little benefit to the River-Side evacuation, we enable the use of contraflow on arcs inbound to evacuation points. We then run the scenario again and find the solution remains the same.

4.5 Insights

4.5.1 Bottlenecks

Our results led to other questions, such as why, in some scenarios, did evacuees not saturate all possible routes leading to the evacuation points? We find that in both evacuation scenarios the evacuating populations funnel through multiple bottlenecks which constrict capacity and the number of vehicles per hour which can traverse that highway network. Once past the bottleneck, evacuees are not restricted by capacity because the sum of the available capacity past the bottleneck is greater than the capacity restriction they just traversed.

Further to the south on I-5, capacity is not used in the Sacramento County base case because the model routes evacuees through the network to minimize their distance they traveled. Figure 4.8 depicts evacuation of Sacramento County without the ability to evacuate people to the East. Capacity constraints in the highways also limit the number of people who are able to evacuate to the North. In Figure 4.8, observe how dark the highway segments are North and West of the I-5/CA-99 split this indicates these arcs are at capacity. Also note that there are highways that are not used in the northwest, this is because people can only evacuate to PointsN if they traverse two highway segments: I-80 west of Sacramento or I-5 north of downtown. Figures 4.15 & 4.16 illustrate the results of these two cuts on the resulting evacuation. This also is a key insight as to why the model routes so few evacuees to PointsN.

4.5.2 Importance of Evacuation to the East and the Bay Area

Table 4.3 shows the capacity per hour of the highway network for flows leaving the region. From this data one can understand why so many evacuees traveled where they did. Again, our model minimized the average distance traveled by each evacuee as well as minimized those stranded and frustrated. In run after run, PointsE received the majority of the evacuees, this is due in part to the ZIP codes we selected to evacuate and also to the fact that there is more highway capacity leading East than there is leading anywhere else.

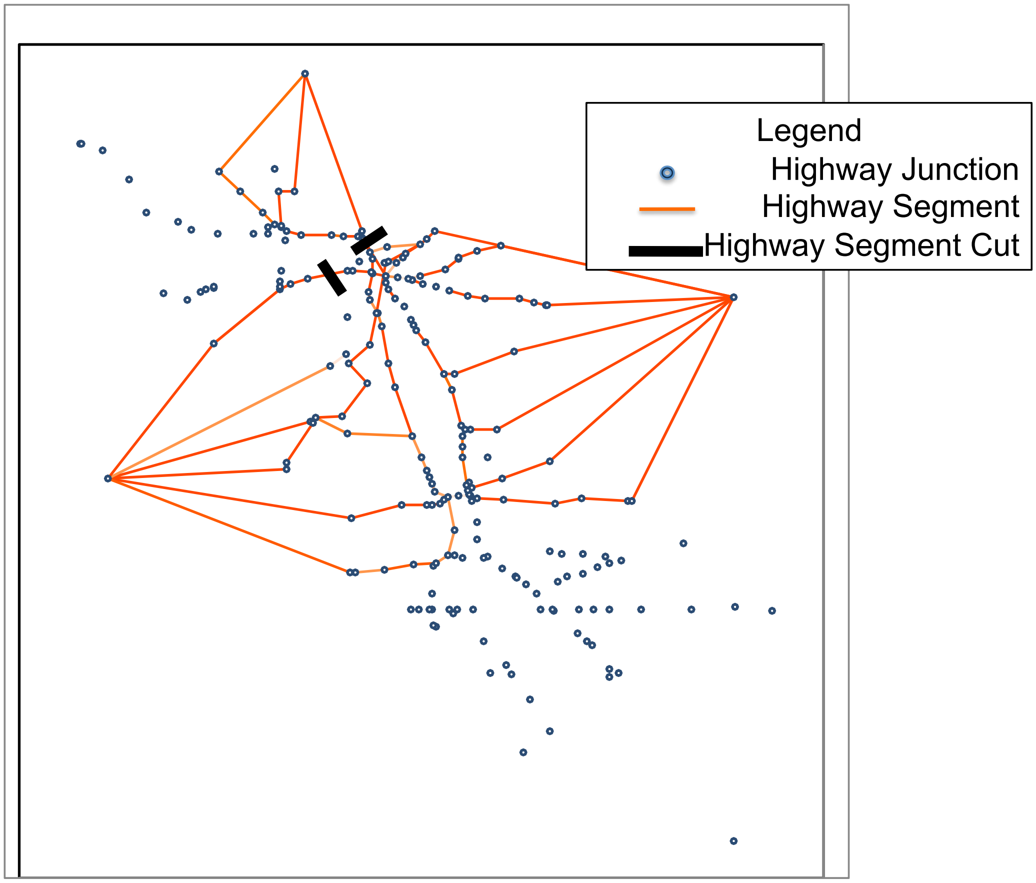


Figure 4.15: The baseline Sacramento County scenario. We add two cuts.

Table 4.3: Evacuation capacity from Yolo, Sacramento, San Joaquin, & Stanislaus counties into each of the evacuation points per hour.

BayArea	PointsN	PointsE	PointsS
15000	10000	17000	16000

The Bay Area was important to the Sacramento County evacuation, receiving the second highest number of evacuees. Together, BayArea and PointsE received 77% of the evacuees in the Sacramento base case. This number dropped to 61% in the River-Side base case, with over 1/3 of the population evacuating East. However, loss of the Bay Area did not change overall evacuation times during the Sacramento County evacuation. This indicates sufficient capacity exists to route evacuees elsewhere in the same amount of time.

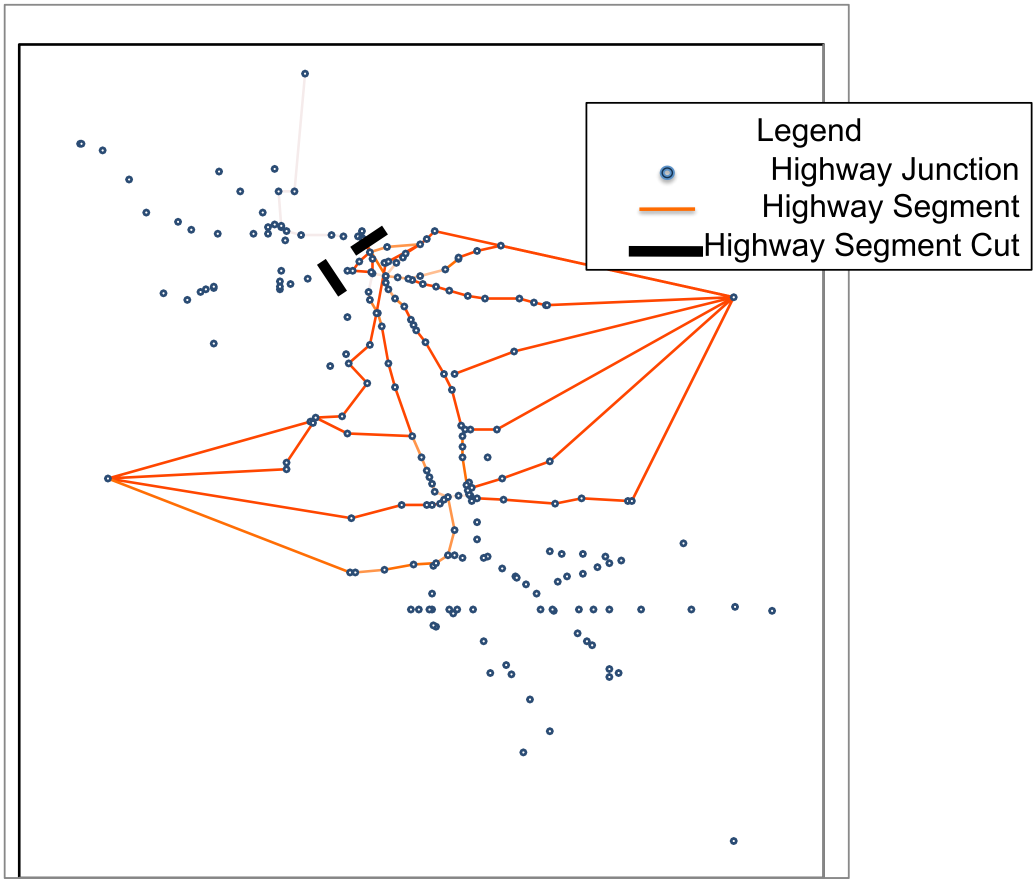


Figure 4.16: The affects of these two cuts are evident in the resulting figure, all ability to evacuate to the North is severed.

4.5.3 Impacts of Flooded Highways

While flooded highways can cause a nuisance to those who live locally or who travel to a specific destination, they are not always factors in limiting the ability to evacuate. Our model assumes perfect information, or advance knowledge of which highways will flood and when. As a result, it pre-plans and routes evacuees in such a manner as to prevent large interruptions in evacuations. In this sense our model provides a “best-case” solution with reference to clearing times. We do not believe that such a model is unreasonable for this region because nearly all highways are elevated and segments of highways which are not elevated are known to emergency services. And while a sudden flooding of these low-lying highways would cause traffic headaches, these inundations would not prevent a regional population from evacuating.

THIS PAGE INTENTIONALLY LEFT BLANK

CHAPTER 5:
Conclusion

We conclude this study by summarizing our results making a few recommendations and proposing several ideas for future research on this topic.

5.1 Summary

We developed two models to identify optimal evacuation routes as well as quantify highway demands during an evacuation in Yolo, Sacramento, San Joaquin and Stanislaus counties. MINATRISK is a single commodity minimum cost network flow model, and MINDIST is a shortest path optimization model which identifies the shortest path from every node in the network to every one of the possible evacuation points. We represent the system of highways in Region IV as a network with ZIP codes providing a supply of evacuees, transshipment nodes as highway junctions, and arcs represent highway segments.

We establish a base case developed using CHP's Standard Operating Procedure which does not allow for contraflow, and apply this case to two baseline scenarios. These scenarios differ only in the subset of ZIP codes which are directed to evacuate in the first epoch. Our model indicates that it is possible to evacuate approximately 1.2 million people from Sacramento County and River-Side evacuations in 24 hours and 15 hours respectively. We find that the shortest route for most evacuees is to travel to evacuation locations to the East and in the Bay Area. We find that loss of PointsE increases evacuation clearing times by 25% in the Sacramento County scenario and 40% in the River-Side scenario, while the loss of the Bay Area does not.

We adjust parameters in the model to cause highway inundations and allow for the use of contraflow. Inundating highways did not substantially change evacuation results however, the inundation of I-5 combined with the loss of PointsE did cause more people to travel to PointsS in the River-Side evacuation than in any other scenario. Furthermore, because we assume two passengers per vehicle, we find people evacuate six hours faster with the use of contraflow. However, because the evacuation of Sacramento County in its entirety is unlikely, and the River-Side evacuation more plausible, we find that our model and the analysis of its results does not support the establishment of contraflow if the evacuating population is not concentrated as in the Sacramento County case.

5.2 Recommendations

As illustrated in the bottleneck discussion, severe limitations exist in the ability for the region to evacuate people to the north. Additional capacity in selected locations would alleviate congestion and provide a more robust evacuation network enabling evacuees from Sacramento County to depart the county faster.

Concerns over highway inundations can be eased by elevating known highways susceptible to flooding. While not a trivial task, doing so can ensure evacuees are able to depart the region over a longer period of time without fear of being cut off from safety. Elevating highways also provides the added benefit of acting as a flood barrier, a second levee, for emergency services to use to halt flooding.

5.3 Future Work

5.3.1 Defining a Realistic Inundation Schedule

Several State and Federal agencies have expressed interest in this work, specifically CHP and the U.S. Geological Survey (USGS). Specifically, USGS has worked extensively on understanding natural disasters in California designing a model of a "worst-case" storm and flooding scenario known as an "ARkStorm" which is based on the storm which flooded the region in the 1860s (Porter & 39 More, 2011). Their extensive work has identified likely highway closures due to mud-slides, etc. this work should be included into this model to scale to an ARkStorm scenario.

5.3.2 Defining Specific Evacuation Destinations

Local experts in evacuations stated early in our research their belief that people tend to travel to places where others live, and that demand is proportional to the population of the destinations. We believe a multi-commodity MINATRISK would provide greater insight into the flows on highways in the region. Such a model would force neighbors to compete for highway capacity in order to reach their respective destinations.

5.3.3 Background Noise

One of our big assumptions revolved around highway capacity: we assumed highways were empty until an evacuation was declared. This can be related to an evacuation in the middle of the night. However, to model an evacuation during the day one would need to include some level of background noise on the highways. We could change our model and reduce capacity on highways in proportion to the population which lives in the adjacent ZIP codes. This would include more realism as not all evacuations occur at night.

5.3.4 On-ramps and Off-ramps

Our model did not constrain evacuees entering the highway. We assumed a constant on-ramp capacity as well as assumed each ZIP code could access the nearest highways at exactly four locations. We could change our model to scale the number of on-ramps based on the population of the ZIP code it services. Our idea is that locations with larger populations are likely to have more on-ramps that service that population and the same could be said for the capacity of those ramps. This would allow for a better estimate of people stranded in their ZIP code because of inability to access the highway within a specified epoch due to capacity constraints.

5.4 Final Thoughts

As observed in Langford (2010, p. 39):

> Over the last few decades, there has been a trend that people migrate toward areas that are disaster prone (*e.g.,* coastal areas, urban wildland interface areas). This suggests that evacuations will become increasingly common as more people inhabit these areas. As such, understanding when to order an evacuation, how long to allow for an evacuation, and how to route individuals in an evacuation will be important for public safety officials....

Recent tragic events such as the Japanese earthquake, tsunami and evacuations over nuclear concerns, and the earthquake in Christchurch, New Zealand illustrate the importance of understanding how people and infrastructure will respond to inordinate situations and demands. To that end we offer our MINATRISK model for optimized highway network evacuation to emergency planners as an additional tool for them to use to gain deeper insights. We provide our analysis on Region IV's system of highways as evidence of the types of analysis which can result from the use of our model.

THIS PAGE INTENTIONALLY LEFT BLANK

References

Ahuja, R. K., Magnanti, T. L., & Orlin, J. B. (1993). *Network Flows*. New Jersey: Prentice Hall.

Ardekani, S., Assavapokee, T., & Lahmar, M. (2006). A Dynamic Transportation Planning Support System for Hurricane Evacuation. In *2006 IEEE Intelligent Transportation Systems Conference* (p. 612-617). September 17-20, 2006; Toronto, Canada.

Baldwin, R. (2006a). *Inland Region Mass Evacuation System.* (Unpublished technical report; preliminary SOP for Mass Evacuations within the Inland Region)

Baldwin, R. (2006b). *Local Government Guide For Interacting With The Inland Region Mass Evacuation & Disaster Relief System.* (Unpublished technical report; supplemental to the Inland Region Mass Evacuation System)

Baldwin, R. (2010). *Conversation with San Joaquin County OES.* (Personal communication 09 November 2010)

Bass, D. J. (2011). *Delta Watershed.* www.deltanationalpark.org/tag/water. (Last accessed: 03 March 2011)

CALFED Bay-Delta Program (CALFED). (2000). *Levee System Integrity Program Plan: Final Programmatic EIS/EIR Technical Appendix.* http://www.water.ca.gov/floodmgmt/dsmo/sab/drmsp/docs/CALFED_ROD_Levee_Plan.pdf. (Last accessed: 28 March 2011)

California Department of Conservation. (2011). *California Geological Survey 2010 Fault Activity Map of California.* http://www.quake.ca.gov/gmaps/FAM/faultactivitymap.html. (Last accessed: 18 March 2011)

California Office of Emergency Services (OES). (2010). *California Mutual Aid Region IV Regional Mass Evacuation Support Concept of Operations.* (Draft December 2010)

California Office of Emergency Services (OES). (2011a). *CAL EMA ”About Us”.* http://www.oes.ca.gov/. (Last accessed: 01 February 2011)

California Office of Emergency Services (OES). (2011b). *Golden Guardian 2011.* http://www.oes.ca.gov/WebPage/oeswebsite.nsf/OESBranchContentPortal?ReadForm&type=Golden%20Guardian&look=Training%20&%20Exercises&Div=Homeland+Security&Branch=Golden%20Guardian. (Last accessed: 07 March 2011)

Center For Sacramento History. (2004). *Sacramento History Timeline.* http://www.sacramentohistory.org/resources_timeline.html. (Last accessed: 20 November 2010)

Fridirici, R., & Shelton, M. (2000). Natural And Human Factors In Recent Central Valley floods. In *Yearbook of the Association of Pacific Coast Geographers* (Vol. 62, p. 53). Honolulu: University of Hawaii Press.

Gaddie, V., Marr, J., & Mierza, M. (2007). *Levee Failures In The Sacramento-San Joaquin River Delta.* http://www.water.ca.gov/floodmgmt/docs/DeltaLeveeFailures_FMA_200709.pdf. (Last accessed: 10 December 2010)

GAMS Development Corporation. (2010). *General Algebraic Modeling System (GAMS) 23.6.* Washington, D.C..

Garcia, A., Llinares, A., Marrero, J., Ortiz, R., & Rodriquez-Losada, J. (2010). The Variable Scale Evacuation Model (VSEM): A New Tool For Fimulating Massive Evacuation Processes During Volcanic Crises. *Natural Hazards Earth System Sciences*, *10*, 747-760.

ILOG. (2007). ILOG CPLEX 11.0 User's Manual [Computer software manual].

Langford, W. P. (2010). *A Space-Time Flow Optimization Model For Neighborhood Evacuation*. M.S. Thesis in Operations Research, Naval Postgraduate School.

Law, A. M. (2007). *Simulation modeling & analysis* (Fourth ed.). New York: McGraw-Hill International.

Mullins, T., Martarano, S., Arteaga, J., & Martarano, S. (1997). *Flood Cleanup Process Continues.* http://www.calema.ca.gov/Executive/Public/oespressroom.nsf/0/4F679D98E7359A2F882576FE007B4D92?OpenDocument. (Last accessed: 23 November 2010)

Porter, K., & 39 More. (2011). *Overview Of The ARkStorm Scenario* (Open-File Report No. 2010-1312). U.S. Geological Survey. (Available electronically from http://pubs.usgs.gov/of/2010/1312/)

Renne, J. L., Sanchez, T. W., & Litman, T. (2008). *National Study On Carless And Special Needs Evacuatoin Planning: A Literature Search.* Available electronically from http://planning.uno.edu/docs/CarelessEvacuationPlanning.pdf. (Last accessed: 21 March 2011)

Sacramento Area Flood Control Agency (SAFCA). (2008). *Sacramento Area Flood History.* http://www.safca.org/history.html. (Last accessed: 20 November 2010)

Santos, G., & Aguirre, B. E. (2005). A Critical Review of Emergency Evacuation Simulation Models. In R. D. Peacock & E. D. Kuligowski (Eds.), *NIST Special Publication 1032: Proceedings of Conference "Building Occupant Movement During Fire Emergencies," June 10-11, 2004. Gaithersburg, Maryland.* (Available electronically from http://dspace.udel.edu:8080/dspace/handle/19716/299)

Sorensen, J. H. (1991). When Shall We Leave? Factors Affecting The Timing Of Evacuation Departures. *International Journal of Mass Emergencies and Disasters*, *9*(2), 153–165.

U.S. Census Bureau. (2000). *2000 Census.* http://factfinder.census.gov/home/saff/main.html. (Last accessed: 20 November 2010)

Xie, C., Waller, S. T., & Kockelman, K. M. (2011). *An Intersection Origin-Destination Flow Optimization Problem For Evacuation Network Design.* http://www.ce.utexas.edu/prof/kockelman/public_html/TRB11IntersectionODFlowOptimization.pdf.

Yusoff, M., Ariffin, J., & Mohamed, A. (2008). Optimization Approaches for Macroscopic Emergency Evacuation Planning: A Survey. In *Proceedings of International Symposium on Information Technology, 2008 (ITSim 2008); Kuala Lumpur, 26-28 August 2008* (p. 1-7).

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX A:
Additional Data Tables

Table A.1: node_location.csv data (headers provided for context)

Node	Longitude	Latitude	Node	Longitude	Latitude
BayArea	-122.2816	37.8243	PointsE	-120.7063	38.8912
PointsN	-122.1246	39.1168	PointsS	-120.367	36.9527
pSAC0050_018	-121.4481118	38.25486921	pSAC00511_608	-121.4862576	38.42001103
pSAC00514_308	-121.4946562	38.45860943	pSAC00517_185	-121.5166734	38.49553766
pSAC00518_651	-121.5221494	38.51615386	pSAC00522_565	-121.5110804	38.56829689
pSAC00525_526	-121.5093983	38.60887364	pSAC00530_5	-121.5500401	38.67105418
pSAC00532_734	-121.5908633	38.67110471	pSAC0054_645	-121.465531	38.32055494
pSAC0120	-121.6854718	38.15969638	pSAC0126_2	-121.5794097	38.12569116
pSAC01611_342	-121.2447603	38.5063045	pSAC01611_366	-121.2443323	38.50621518
pSAC01614_066	-121.1959046	38.49682135	pSAC01614_094	-121.1954099	38.49670129
pSAC01619_48	-121.0986485	38.49638425	pSAC0162_53	-121.3989866	38.54708399
pSAC01621_784	-121.0595314	38.48572655	pSAC01623_81	-121.0274799	38.48081432
pSAC01623_948	-121.0244877	38.48082702	pSAC0164_202	-121.3702544	38.53860164
pSAC0166_22	-121.3349325	38.52900486	pSAC0168_342	-121.2978598	38.51889221
pSAC0500	-121.5158707	38.57146136	pSAC05012_469	-121.2709297	38.60897174
pSAC05012_496	-121.2704951	38.60913087	pSAC05015_759	-121.2171043	38.63090997
pSAC05019_41	-121.1532786	38.64199233	pSAC0502_507	-121.4735044	38.55887761
pSAC0504_307	-121.441944	38.55591624	pSAC0506_084	-121.409214	38.55364849
pSAC0507_734	-121.3794968	38.55886163	pSAC0509_505	-121.3081677	38.57855913
pSAC0513_397	-121.4432931	38.5975463	pSAC0514_743	-121.4268317	38.61124123
pSAC0515_498	-121.419661	38.6200844	pSAC0800	-121.5478715	38.5984408
pSAC08010_943	-121.3781256	38.64617082	pSAC08012_452	-121.3605397	38.66076533
pSAC08012_476	-121.3602413	38.6610301	pSAC08014_393	-121.3373924	38.68233906
pSAC0802_554	-121.5172262	38.62512918	pSAC0805_363	-121.4706082	38.64166292
pSAC09910_07	-121.362163	38.37637112	pSAC09912_761	-121.3887115	38.40906334
pSAC09913_784	-121.395201	38.42305755	pSAC09914_869	-121.4018733	38.43789039
pSAC09917_656	-121.4229765	38.4742803	pSAC09919_747	-121.4477018	38.49760985
pSAC09921_944	-121.467753	38.52492028	pSAC09923_128	-121.4739148	38.54118259
pSAC09924_328	-121.4735044	38.55887761	pSAC0993_525	-121.3123931	38.29106925
pSAC09932_124	-121.5401494	38.66723129	pSAC09932_27	-121.536942	38.66241199
pSAC09933_324	-121.5402528	38.68475699	pSAC1041_61	-121.2827094	38.29128754
pSAC10412_183	-121.1143996	38.35012093	pSAC1600	-121.751548	38.0266894
pSAC1601_39	-121.7511298	38.04642408	pSAC16010_68	-121.6700725	38.16728477
pSAC16014_79	-121.5948121	38.17244286	pSAC16022_08	-121.5249046	38.26243533
pSAC16026_96	-121.5763917	38.32033194	pSAC16031_54	-121.5198846	38.36953068
pSAC16037_77	-121.5009876	38.45835343	pSAC16047_47	-121.4754026	38.59719125
pSAC16047_6	-121.4772091	38.59603848	pSAC16048_17	-121.4681596	38.60033431
pSAC1609_78	-121.676438	38.15519003	pSJ0040	-121.569888	37.89081017

Table A.2: node_location.csv data continued (headers provided for context)

Node	Longitude	Latitude	Node	Longitude	Latitude
pSJ00412_61	-121.3584042	37.92692267	pSJ00412_64	-121.3578583	37.92692354
pSJ00413_427	-121.3435697	37.92694904	pSJ00414_6	-121.3204578	37.93067881
pSJ00415_318	-121.3122409	37.94359705	pSJ00416_059	-121.3008174	37.94845454
pSJ00417_684	-121.2713712	37.95343409	pSJ00420_69	-121.2176725	37.94493564
pSJ00425	-121.1456364	37.94213306	pSJ00433_1	-120.9997922	37.93003021
pSJ0048_7	-121.4283248	37.92669205	pSJ0050	-121.3336178	37.59075311
pSJ00511_801	-121.3421386	37.75953493	pSJ00512_623	-121.3318647	37.76731116
pSJ00514_84	-121.30186	37.78882	pSJ00519_808	-121.2813714	37.85880391
pSJ00528_533	-121.3355009	37.96424758	pSJ00529_99	-121.343723	37.98488937
pSJ0053_56	-121.343095	37.63812	pSJ00531_451	-121.3515713	38.00477112
pSJ00532_66	-121.3589856	38.02130593	pSJ00535_513	-121.3737412	38.06087465
pSJ00539_574	-121.398168	38.116211	pSJ01218_871	-121.2377749	38.13772447
pSJ01223_286	-121.1626202	38.137959	pSJ0261_897	-121.2321518	37.97403159
pSJ02615_06	-121.0147902	38.04996096	pSJ0266_85	-121.149469	38.00073121
pSJ0330	-121.2855301	37.62902902	pSJ0334_985	-121.343137	37.684879
pSJ0335_2	-121.3432918	37.68168863	pSJ0880_57	-121.2420498	37.98984409
pSJ0886_518	-121.1887711	38.05837897	pSJ0990	-121.1100348	37.73028285
pSJ09912_95	-121.2202039	37.88127814	pSJ09917_12	-121.234918	37.940427
pSJ09918_3	-121.2402044	37.95699387	pSJ09918_3	-121.2384902	37.95255003
pSJ09918_62	-121.2402044	37.95699387	pSJ0992_659	-121.1469672	37.75468127
pSJ09920_93	-121.250119	37.9847	pSJ09921_97	-121.245639	37.970093
pSJ09928_31	-121.25969	38.06105181	pSJ09930_12	-121.2601123	38.08720636
pSJ09932_14	-121.257663	38.116347	pSJ09932_46	-121.261389	38.14781424
pSJ09933_74	-121.2522734	38.13762139	pSJ09939_34	-121.2881304	38.24563887
pSJ0996_39	-121.1898889	37.78475688	pSJ0999_75	-121.2177366	37.83478247
pSJ1201_625	-121.2820155	37.78813451	pSJ12015_916	-121.0138979	37.79857437
pSJ12017_946	-120.9825306	37.79426729	pSJ1202_845	-121.2606335	37.78333899
pSJ1206_155	-121.2002233	37.78353264	pSJ1321_164	-121.3808729	37.63807367
pSJ1322_684	-121.3531522	37.63792265	pSJ1325_855	-121.2953493	37.63802655
pSJ1327_108	-121.273769	37.63831221	pSJ2050	-121.5571095	37.74319176
pSJ2054_547	-121.4767158	37.74876055	pSJ2059_13	-121.3965625	37.76500077
pSJ5800	-121.3410516	37.59646839	pSJ58015_344	-121.573348	37.74203
pSJ5804_344	-121.4028813	37.63911325	pSTA0040	-120.9263094	37.94485516

Table A.3: node_location.csv data continued (headers provided for context)

Node	Longitude	Latitude	Node	Longitude	Latitude
pSTA0047_296	-120.7954952	37.9372949	pSTA0048_025	-120.7858797	37.93732536
pSTA0050	-121.0890991	37.2459914	pSTA00515_855	-121.1807512	37.46383046
pSTA0330	-121.01602	37.30350024	pSTA03312_37	-121.1212556	37.46181907
pSTA03314_35	-121.1392298	37.48668958	pSTA03319_936	-121.2007551	37.55040508
pSTA0336_73	-121.0700323	37.39124474	pSTA0990_041	-120.8230979	37.4635425
pSTA0991_558	-120.848967	37.47449663	pSTA09910_034	-120.9372922	37.5745354
pSTA09915_753	-121.002433	37.63533909	pSTA09915_79	-121.006726	37.639342
pSTA09920_222	-121.0532435	37.68344775	pSTA09922_558	-121.0812845	37.70905108
pSTA09924_491	-121.1065583	37.72781144	pSTA0996_995	-120.8952555	37.53987819
pSTA0998_16	-120.9104575	37.55093052	pSTA10830_501	-120.9687095	37.73271516
pSTA10833_38	-120.9226884	37.73710837	pSTA10836_151	-120.8815917	37.75472381
pSTA10838_251	-120.847135	37.768021	pSTA1200	-120.9233269	37.79356197
pSTA12016_907	-120.6417859	37.82241116	pSTA1203_79	-120.858557	37.7842081
pSTA1206_84	-120.8164334	37.77617883	pSTA13212_9	-121.0398357	37.63858456
pSTA13218_4	-120.9343044	37.63828463	pSTA1322_435	-121.2287412	37.64126441
pSTA13220_64	-120.893295	37.63836216	pSTA13223_144	-120.8476723	37.6387246
pSTA13228	-120.7595765	37.63831123	pSTA13235_98	-120.6200509	37.63896528
pSTA13243_719	-120.4965674	37.64603574	pSTA13243_766	-120.4959318	37.64655082
pSTA13250_966	-120.3939754	37.63766777	pSTA1650	-120.8490224	37.45217896
pSTA2195	-120.9949583	37.71516897	pYOL0050	-121.6259038	38.67322197
pYOL00517_616	-121.8795805	38.79428817	pYOL0054_493	-121.7094302	38.67359078
pYOL0059_391	-121.7830965	38.70215161	pYOL0059_411	-121.7833441	38.70238159
pYOL0160_32	-122.32689	38.92405	pYOL0160_632	-122.3228299	38.92391029
pYOL01612_27	-122.1897902	38.82580862	pYOL01619_154	-122.1445999	38.73538513
pYOL01625_336	-122.0543146	38.7083048	pYOL01628_3	-122.0164557	38.68886558
pYOL01637_94	-121.8437627	38.6778947	pYOL01640_57	-121.802541	38.67765315
pYOL01641_7	-121.8024171	38.69411043	pYOL01644_69	-121.8186813	38.73540172
pYOL0165_009	-122.266182	38.90665418	pYOL0455_8	-121.7855485	38.85598621
pYOL0800	-121.7384522	38.53782033	pYOL0802_958	-121.6910688	38.55373299
pYOL0808_917	-121.5820943	38.57361129	pYOL0809_817	-121.5664648	38.57589995
pYOL0840	-121.6306397	38.31324068	pYOL08411_77	-121.582932	38.44679529
pYOL0844_57	-121.5848569	38.34259318	pYOL1130_56	-121.76887	38.522874
pYOL1130	-121.768707	38.53092751	pYOL1131_082	-121.7681903	38.54636625
pYOL11310_717	-121.7515175	38.68437879	pYOL11311_438	-121.7651354	38.69651392
pYOL11311_606	-121.7651798	38.69881554	pYOL11318_66	-121.7743281	38.7929247
pYOL11321_16	-121.7281136	38.79241239	pYOL1133_052	-121.7677506	38.57495281
pYOL1138_818	-121.7533225	38.65684523	pYOL1280	-122.095486	38.51300963
pYOL1284_59	-122.0283167	38.49465039	pYOL1287_55	-121.9912959	38.51755193
pYOL1288_42	-121.9766324	38.52287475	pYOL505_10_62	-121.955888	38.372122
pYOL5050	-121.953072	38.52565516	pYOL5050_39	-121.9531	38.53129
pYOL50510_57	-121.9425327	38.67824699	pYOL50522_29	-121.9398646	38.84765179

Table A.4: node_location.csv data continued (headers provided for context)

Node	Longitude	Latitude	Node	Longitude	Latitude
z95937	-121.94518	38.931025	z95912	-122.02725	38.97159
z95864	-121.37809	38.587805	z95843	-121.3698	38.716874
z95842	-121.349	38.687718	z95841	-121.34361	38.66152
z95838	-121.4417	38.641223	z95837	-121.60207	38.700244
z95836	-121.54983	38.707236	z95835	-121.52061	38.664824
z95834	-121.50466	38.642805	z95833	-121.49623	38.616891
z95832	-121.49643	38.464667	z95831	-121.53059	38.494971
z95830	-121.2651	38.498156	z95829	-121.34715	38.476196
z95828	-121.4024	38.484747	z95827	-121.32515	38.566506
z95826	-121.37492	38.550098	z95825	-121.40726	38.594205
z95824	-121.44378	38.518356	z95823	-121.44561	38.477508
z95822	-121.49201	38.51394	z95821	-121.38181	38.623304
z95820	-121.44663	38.535795	z95819	-121.44099	38.568855
z95818	-121.49285	38.556576	z95817	-121.45996	38.551106
z95816	-121.46827	38.571661	z95815	-121.44553	38.611854
z95814	-121.49125	38.580255	z95776	-121.74189	38.681254
z95758	-121.43673	38.406432	z95742	-121.18367	38.607756
z95695	-121.80944	38.697238	z95694	-121.97757	38.537434
z95693	-121.23708	38.382367	z95690	-121.56507	38.240477
z95686	-121.44032	38.228976	z95683	-121.10036	38.492811
z95673	-121.44874	38.688069	z95670	-121.28247	38.605355
z95662	-121.2231	38.682803	z95660	-121.37656	38.676103
z95655	-121.28737	38.558073	z95641	-121.60428	38.161756
z95639	-121.51487	38.367276	z95638	-121.16166	38.317665
z95632	-121.29723	38.267544	z95627	-121.99929	38.744062
z95630	-121.15783	38.672127	z95628	-121.26529	38.654803
z95626	-121.45433	38.727451	z95624	-121.36059	38.421068
z95621	-121.3081	38.695252	z95616	-121.73655	38.549256
z95615	-121.54853	38.333568	z95612	-121.57819	38.383366
z95610	-121.27125	38.696912	z95608	-121.32702	38.628371
z95607	-122.125	38.706727	z95606	-122.21486	38.857328
z95387	-121.24702	37.539768	z95386	-120.73812	37.645632
z95385	-121.26784	37.609781	z95382	-120.8516	37.523901
z95380	-120.85196	37.48858	z95376	-121.42399	37.728417
z95367	-120.94365	37.731272	z95366	-121.12546	37.742895
z95363	-121.14555	37.477477	z95361	-120.84756	37.776528
z95360	-121.0314	37.312014	z95358	-121.05181	37.622898
z95357	-120.9061	37.667196	z95356	-121.02187	37.704138
z95355	-120.95566	37.673513	z95337	-121.23578	37.782332
z95336	-121.21416	37.812815	z95330	-121.28541	37.816876
z95329	-120.42421	37.694235	z95326	-120.86419	37.59471

Table A.5: node_location.csv data continued (headers provided for context)

Node	Longitude	Latitude	Node	Longitude	Latitude
z95323	-120.7141	37.6194	z95320	-121.00179	37.797806
z95316	-120.78463	37.552329	z95313	-121.05649	37.413659
z95307	-120.95064	37.584282	z95258	-121.306	38.154118
z95242	-121.32282	38.132618	z95240	-121.25039	38.12463
z95237	-121.14855	38.162818	z95236	-121.05675	38.018456
z95231	-121.27978	37.882742	z95230	-120.82329	37.959439
z95227	-121.05361	38.205817	z95220	-121.23505	38.200193
z95219	-121.40022	38.004922	z95215	-121.19064	37.955474
z95212	-121.24213	38.038906	z95210	-121.29722	38.025086
z95209	-121.34378	38.035499	z95207	-121.3237	38.004172
z95206	-121.3025	37.922024	z95205	-121.26401	37.962873
z95204	-121.3147	37.974273	z95203	-121.30735	37.954823
z94571	-121.72075	38.156909	z95691	-121.54496	38.569193
z95605	-121.52805	38.592155			

Table A.6: Tables of Sacramento County evacuation duration case-by-case for every scenario.

Sacramento County Evacuation (Hrs.)					
	CFM=0	CFM=50	CFM=100	CFM=150	CFM=200
PPV=1	39	33	30	30	30
PPV=1.5	27	24	21	21	21
PPV=2	21	18	15	15	15
PPV=2.5	15	15	12	12	12
PPV=3	15	12	12	12	12
PPV=3.5	12	9	9	9	9
PPV=4	9	9	9	9	9

Sacramento County Loss of PointsE (Hrs.)					
	CFM=0	CFM=50	CFM=100	CFM=150	CFM=200
PPV=1	54	60	54	48	48
PPV=1.5	36	36	33	33	33
PPV=2	27	27	24	27	27
PPV=2.5	21	24	21	21	21
PPV=3	18	21	18	18	18
PPV=3.5	15	18	15	15	15
PPV=4	15	15	12	12	12

Sacramento County Loss of BayArea (Hrs.)					
	CFM=0	CFM=50	CFM=100	CFM=150	CFM=200
PPV=1	39	39	39	36	36
PPV=1.5	27	24	27	24	24
PPV=2	21	18	18	18	18
PPV=2.5	18	15	15	15	15
PPV=3	15	12	12	12	12
PPV=3.5	12	12	12	12	12
PPV=4	12	9	9	9	9

Sacramento County Loss of I-5 (Hrs.)					
	CFM=0	CFM=50	CFM=100	CFM=150	CFM=200
PPV=1	39	36	33	30	30
PPV=1.5	27	24	21	21	21
PPV=2	21	18	18	15	15
PPV=2.5	15	15	12	12	12
PPV=3	15	12	12	12	12
PPV=3.5	12	12	9	9	9
PPV=4	9	9	9	9	9

Table A.7: Tables of Sacramento County evacuation duration case-by-case for every scenario continued.

Sacramento County Loss of CA-99 (Hrs.)					
	CFM=0	CFM=50	CFM=100	CFM=150	CFM=200
PPV=1	39	33	33	30	30
PPV=1.5	27	24	21	21	21
PPV=2	21	18	18	15	15
PPV=2.5	15	15	15	12	12
PPV=3	15	12	12	12	12
PPV=3.5	12	9	9	9	9
PPV=4	9	9	9	9	9

Sacramento County Loss of I-5 & CA-99 (Hrs.)					
	CFM=0	CFM=50	CFM=100	CFM=150	CFM=200
PPV=1	39	39	36	36	36
PPV=1.5	27	24	24	24	24
PPV=2	21	18	18	18	18
PPV=2.5	18	15	15	15	15
PPV=3	15	12	12	12	12
PPV=3.5	12	12	9	9	9
PPV=4	9	9	9	9	9

Sacramento County Loss of PointsE & I-5 (Hrs.)					
	CFM=0	CFM=50	CFM=100	CFM=150	CFM=200
PPV=1	57	60	57	54	54
PPV=1.5	39	42	36	36	36
PPV=2	30	33	27	27	27
PPV=2.5	24	24	21	21	21
PPV=3	21	21	18	18	18
PPV=3.5	18	18	18	15	15
PPV=4	15	15	15	12	12

Table A.8: Tables of River-Side ZIP code evacuation duration case-by-case for every scenario.

River-Side Evacuation (Hrs.)					
	CFM=0	CFM=50	CFM=100	CFM=150	CFM=200
PPV=1	27	27	27	27	27
PPV=1.5	18	18	18	18	15
PPV=2	12	15	12	12	15
PPV=2.5	12	9	9	9	9
PPV=3	9	9	9	9	9
PPV=3.5	9	9	9	9	9
PPV=4	6	6	6	6	6

River-Side Loss of PointsE (Hrs.)					
	CFM0	CFM 50	CFM 100	CFM 150	CFM 200
PPV=1	36	39	36	36	36
PPV=1.5	24	27	27	27	24
PPV=2	18	21	18	18	21
PPV=2.5	15	15	15	15	15
PPV=3	12	15	12	12	12
PPV=3.5	12	12	12	12	12
PPV=4	9	9	9	9	9

River-Side Loss of BayArea (Hrs.)					
	CFM=0	CFM=50	CFM=100	CFM=150	CFM=200
PPV=1	33	36	36	36	36
PPV=1.5	21	24	24	24	24
PPV=2	18	18	18	18	18
PPV=2.5	15	15	15	15	15
PPV=3	12	12	12	12	12
PPV=3.5	9	9	9	12	9
PPV=4	9	9	9	9	9

River-Side Loss of I-5 (Hrs.)					
	CFM=0	CFM=50	CFM=100	CFM=150	CFM=200
PPV=1	30	30	27	27	27
PPV=1.5	18	18	18	18	18
PPV=2	15	15	15	15	15
PPV=2.5	12	9	9	9	9
PPV=3	9	9	9	9	9
PPV=3.5	9	9	6	9	9
PPV=4	9	6	6	6	6

Table A.9: Tables of River-Side ZIP code evacuation duration case-by-case for every scenario.

River-Side Loss of CA-99 (Hrs.)					
	CFM=0	CFM=50	CFM=100	CFM=150	CFM=200
PPV=1	30	27	27	27	27
PPV=1.5	21	18	18	18	18
PPV=2	15	15	12	15	15
PPV=2.5	12	9	9	9	9
PPV=3	12	9	9	9	9
PPV=3.5	9	9	6	6	9
PPV=4	9	6	6	6	6

River-Side Loss of I-5 & CA-99 (Hrs.)					
	CFM=0	CFM=50	CFM=100	CFM=150	CFM=200
PPV=1	30	27	27	27	27
PPV=1.5	21	18	18	18	18
PPV=2	18	15	15	15	15
PPV=2.5	12	9	9	9	9
PPV=3	12	9	9	9	9
PPV=3.5	9	9	6	6	9
PPV=4	9	6	6	6	6

River-Side Loss of PointsE & I-5 (Hrs.)					
	CFM=0	CFM=50	CFM=100	CFM=150	CFM=200
PPV=1	48	42	42	42	42
PPV=1.5	30	30	27	27	27
PPV=2	24	21	21	21	21
PPV=2.5	18	15	15	15	15
PPV=3	15	15	15	15	15
PPV=3.5	12	12	12	12	12
PPV=4	12	9	9	9	9

Table A.10: g.csv data (headers provided for context)

evacuation point
BayArea
PointsS
PointsN
PointsE

Table A.11: inundation_schedule.csv data (headers provided for context)

Highway Junction	Epoch
pSJ1201_625	t2
pSJ00514_84	t2
pSJ00519_808	t2
pSJ12015_916	t2
pSJ0996_39	t2
pSJ0999_75	t2

Table A.12: evaclist.csv data (headers provided for context)

ZIP code	Epoch	ZIP code	Epoch
z95864	t1	z95843	t1
z95842	t1	z95841	t1
z95838	t1	z95837	t1
z95836	t1	z95835	t1
z95834	t1	z95833	t1
z95832	t1	z95830	t1
z95829	t1	z95828	t1
z95827	t1	z95826	t1
z95825	t1	z95824	t1
z95823	t1	z95822	t1
z95821	t1	z95820	t1
z95819	t1	z95818	t1
z95817	t1	z95816	t1
z95815	t1	z95814	t1
z95758	t1	z95742	t1
z95693	t1	z95690	t1
z95683	t1	z95673	t1
z95670	t1	z95662	t1
z95660	t1	z95655	t1
z95641	t1	z95639	t1
z95638	t1	z95632	t1
z95630	t1	z95628	t1
z95626	t1	z95624	t1
z95621	t1	z95615	t1
z95610	t1	z95608	t1

Initial Distribution List

1. Defense Technical Information Center
   Ft. Belvoir, VA

2. Dudly Knox Library
   Naval Postgraduate School
   Monterey, CA

3. Director, Studies and Analysis Division, MCCDC, Code C45
   Quantico, VA

4. Mr. Jim Brown, Regional Administrator CAL EMA
   Mather, CA

5. Mr. Ron Baldwin, SJC OES
   Stockton, CA

6. Mr. Frank Calvillo, PSA DHS
   Sacramento, CA

7. Ms. Norma J. Schroeder, DFA
   Sacramento, CA

8. LCDR Andrew Silcox, CHP
   Services Section
   Sacramento, CA

9. Dr. Anne Wein, U.S.G.S.
   Menlo Park, CA

10. Mr. Tremain Downey, CALTRANS
    Sacramento, CA