

HYDROLOGIC AND HYDRAULIC REPORT

**Puna Flood Study Project
Puna, Hawai'i**



**Prepared for:
County of Hawai'i
Department of Public Works**

**Prepared by:
Oceanit Laboratories, Inc.
828 Fort Street Mall, Suite 600
Honolulu, Hawai'i 96813**

August 2013



CONTENTS

1	INTRODUCTION	1
1.1	BACKGROUND	1
1.2	PURPOSE AND SCOPE.....	1
1.3	METHODOLOGY.....	2
1.4	PREVIOUS STUDIES	3
1.5	ACKNOWLEDGEMENTS.....	3
2	STUDY AREA DESCRIPTION	4
2.1	STUDY AREA OVERVIEW	4
2.2	TOPOGRAPHY, VEGETATION, AND LAND USE	4
2.2.1	Geology and Climate	6
2.2.2	Water Resources and Hydrology.....	7
2.3	HYDROLOGIC DATA.....	7
2.3.1	Rain Gages.....	7
2.3.2	Stream Gages	8
2.3.3	Field Survey.....	8
2.4	FLOODING PROBLEMS IN THE STUDY AREA	10
2.5	SOUTH KŪLANI FLOOD DIVERSION STRUCTURE	10
3	HYDROLOGIC ANALYSIS.....	11
3.1	HEC-HMS MODEL OVERVIEW.....	11
3.2	GEOSPATIAL INFORMATION USED.....	11
3.3	METEOROLOGICAL EVENTS.....	22
3.4	BASIN LOSS	32
3.5	ESTIMATION OF TIME OF CONCENTRATIONS	40
3.6	HYDROGRAPH TRANSFORM PARAMETERS	41
3.7	MODEL CALIBRATION	44
3.8	HYDROLOGIC ANALYSIS RESULTS.....	48
4	HYDRAULIC ANALYSIS	50
4.1	FLO-2D MODEL OVERVIEW	50
4.2	FLO-2D MODEL SETUP.....	50



4.2.1	Topographic Database.....	50
4.2.2	Sub-domains and Grid Size	51
4.2.3	Hydrologic Input.....	51
4.2.4	Streams.....	54
4.2.5	Water Diversion Systems	58
4.2.6	Bridges and Culverts	63
4.3	FLO-2D MODEL CALIBRATION	66
4.4	HYDRAULIC ANALYSIS RESULTS	67
4.4.1	Water Diversion System Assessment	67
4.4.2	FLO-2D Model Calibration Result.....	67
4.4.3	FLO-2D Model Results.....	74
4.5	DETERMINATION OF FLOODPLAIN BOUNDARIES	90
5	CONCLUSION AND LIMITATION	91
REFERENCES.....		93
APPDENDIX A - FLO-2D HYDROLOGGY MODEL DEVELOPMENT		
APPDENDIX B - FIELD SURVEY SOUTH KULANI BRIDGE DIVERSION STRUCTURE		
APPDENDIX C - FIELD SURVEY ROADWAY CULVERTS & BRIDGE CROSSINGS		



LIST OF FIGURES

Figure ES-1. Watershed and Junction Locations.....	ix
Figure 2 - 1. Location Map for Puna Study Area.	5
Figure 3 - 1. Puna Study Sub-watershed.	13
Figure 3 - 2. Sub-basin Centroids for Puna.....	14
Figure 3 - 3. HEC-HMS Model Layout for Puna Study Area.	15
Figure 3 - 4. HEC-HMS Model Structure for Puna Study Area.	16
Figure 3 - 5. Junctions of Interest for Puna Study Area.....	17
Figure 3 - 6. Rainfall of Each Sub-watershed for 10-yr Storm Return Period.....	23
Figure 3 - 7. Rainfall of Each Sub-watershed for 50-yr Storm Return Period.....	24
Figure 3 - 8. Rainfall of Each Sub-watershed for 100-yr Storm Return Period.....	25
Figure 3 - 9. Rainfall of Each Sub-watershed for 500-yr Storm Return Period.....	26
Figure 3 - 10. Designed 100-year 24-hour Rainfall Distribution for Sub-watershed 43 (Typical Hyetograph).....	27
Figure 3 - 11. Soil Type for Puna Study Area.	35
Figure 3 - 12. Saturated Soil Conductivities for Puna Watershed.....	36
Figure 3 - 13. Rain Gages Thiessen Polygon for November 1, ato 2, 2000, Storm.....	45
Figure 4 - 1. FLO-2D Model Sub-domains.	52
Figure 4 - 2 Hydrograph Inflow locations for the sub-watersheds.	53
Figure 4 - 3. Typical Steady State Inflow Hydrographs.....	54
Figure 4 - 4. Keaau Stream locations from Hawaii State Geographic Information System. ..	55
Figure 4 - 5. 40th Avenue at 1400 Feet North of the Intersection with Pohuku Drive.....	56
Figure 4 - 6. 40th Avenue at 1800 Feet South of the Intersection with Pohuku Drive.	56
Figure 4 - 7. The Intersection between the 39th Avenue and Pohaku Drive.	57
Figure 4 - 8. Keaau Stream before Crossing the Intersection between the 39 th Avenue and Pohaku Drive.....	57
Figure 4 - 9. Potential Flooding Problem at Hawaiian Acres by HACA.....	60
Figure 4 - 10. Diversionary Structure Layout.....	61
Figure 4 - 11. Photo of Rock Wall.....	62
Figure 4 - 12. One Section of the Rock Wall.....	62
Figure 4 - 13. Failed Section of Rock Wall.....	63



Figure 4 - 14. Satellite Image of the Area around the Hydraulic Division System.....	64
Figure 4 - 15. Surveyed Hydraulic Structure Locations.....	65
Figure 4 - 16. Comparison of Flow Depth Downstream the South Kūlani Bridge.....	68
Figure 4 - 17. Flow Surface Elevation in the Case of With- and Without-structure.....	69
Figure 4 - 18. Flooded Roads at Puna District.	70
Figure 4 - 19. Flood Waters Washed Away One Stretch of the Road at Hawaiian Acres.	71
Figure 4 - 20. Flood Waters Washed over the Kukui Camp Road.....	71
Figure 4 - 21. Field Visit Locations for Storm Event of November 1 to 2, 2000.....	73
Figure 4 - 22. Damaged Road Surface at Kuauli Road.....	74
Figure 4 - 23. Outflow Boundary Cross-section Locations.	76
Figure 4 - 24. Flood Profile for Keaau Stream.	78
Figure 4 - 25. Flood Profile for Keaau Stream (continued).....	79
Figure 4 - 26. Flood Profile for Keaau Stream (continued).....	80
Figure 4 - 27. Flood Profile for Keaau Stream (continued).....	81
Figure 4 - 28. Flow Depth for 10-Year Flood.	82
Figure 4 - 29. Flow Depth for 50-Year Flood.	83
Figure 4 - 30. Flow Depth for 100-Year Flood.	84
Figure 4 - 31. Flow depth for 500-Year Flood.	85
Figure A - 1. FLO-2D Model Subdomains.	A-1
Figure A - 2. Typical 24-hour, 100-year Accumulated Rainfall Distribution.	A-2
Figure B - 1 Hydraulic Structure Survey Points.....	B-2
Figure B - 2 Hydraulic Diversion Structures.....	B-3
Figure B - 3. Surveyed Cross-sections.....	B-4
Figure B - 4. Surveyed Cross-sections (continued).	B-5
Figure B - 5.. Surveyed Cross-sections (continued).	B-6
Figure B - 6. Surveyed Cross-sections (continued).	B-7
Figure B - 7. Surveyed Cross-sections (continued).	B-8
Figure B - 8. Surveyed Cross-sections (continued).	B-9
Figure B - 9. Surveyed Cross-sections (continued).	B-10
Figure B - 10. Surveyed Cross-sections (continued).	B-11
Figure B - 11. Surveyed Cross-sections (continued).	B-12
Figure B - 12. Surveyed Cross-sections (continued).	B-13



Figure B - 13. Surveyed Cross-sections (continued).....	B-14
Figure C- 1. Benchmark for GPS Instrument Error Correction.	C-1
Figure C- 2. Photo of the Keaa-Pahoa Road Culvert 1.....	C-2
Figure C- 3. Cross-sections of the Keaa-Pahoa Road Culvert 1.....	C-2
Figure C- 4. Rating Curve of the Keaa-Pahoa Road Culvert 1.	C-3
Figure C- 5. Keaa-Pahoa Road Culvert 2.	C-3
Figure C- 6. Rating Curve of Keaa-Pahoa Road Culvert 2.....	C-4
Figure C- 7. Waipahoehoe Stream Bridge.	C-4
Figure C- 8. Rating Curve of Waipahoehoe Stream Bridge.....	C-5
Figure C- 9. Photo of Moho Road Culvert 1.....	C-5
Figure C- 10. Cross-section of Moho Road Culvert 1.....	C-6
Figure C- 11. Rating Curve of Moho Road Culvert 1.	C-6
Figure C- 12. Photo of Moho Road Culvert 2 (Downstream side).....	C-7
Figure C- 13. Cross-section of Moho Road Culvert 2.....	C-7
Figure C- 14. Rating Curve of Moho Road Culvert 2.	C-8
Figure C- 15. Photo of South Kūlani Road Bridge.....	C-8
Figure C- 16. Cross-section of South Kūlani Road Bridge.....	C-9
Figure C- 17. Rating Curve of South Kūlani Road Bridge.	C-9
Figure C- 18. Photo of Enos Road Culvert.	C-10
Figure C- 19. Cross-section of Enos Road Culvert.	C-10
Figure C- 20. Rating Curve of Enos Road Culvert.	C-11
Figure C- 21. Cross-section of South Pszyk Road Culvert 1.....	C-11
Figure C- 22. Rating Curve of South Pszyk Road Culvert 1.	C-12
Figure C- 23. Photo of South Pszyk Road Culvert 2.....	C-12
Figure C- 24. Cross-section of South Pszyk Road Culvert 2.....	C-13
Figure C- 25. Rating Curve of South Pszyk Road Culvert 2.	C-13
Figure C- 26. Cross-section of South Kopua Road Bridge.....	C-14
Figure C- 27. Rating Curve of South Kopua Road Bridge.	C-14
Figure C- 28. Cross-section of South Kopua Road Culvert.....	C-15
Figure C- 29. Rating Curve of South Kopua Road Culvert.....	C-15
Figure C- 30. Photo of North Oshiro Road Bridge 2.	C-16



Figure C- 31. Cross-section of North Oshiro Road Bridge 2.	C-16
Figure C- 32. Rating Curve of North Oshiro Road Bridge 2.	C-17



LIST OF TABLES

Table ES-1. Peak Discharges for Storm Events.....	viii
Table 2 - 1. Rain Gages.	8
Table 3 - 1. Sub-Watersheds, Areas and Centroids.....	18
Table 3 - 2. Sub-watersheds, Junctions, and Drainage Areas of Puna Study Area.....	20
Table 3 - 3. Rainfall for Sub-watersheds Extracted from Atlas 14.	28
Table 3 - 4. Soil Types in Puna Study Area.	34
Table 3 - 5. Green-Ampt Infiltration Parameters Determination for Puna Study Area.....	37
Table 3 - 6. Average Saturated Hydraulic Conductivities for Sub-watersheds.	39
Table 3 - 7. Time of Concentration Values for Puna Study Area.....	42
Table 3 - 8. Gage Depth and Time Weights for November 1 to 2, 2000, Storm.....	46
Table 3 - 9. Comparison of Model Results for November 1 to 2, 2000, Storm.....	47
Table 4 - 1 Names of the Surveyed Bridges and Culverts.	66
Table 4 - 2. FLO-2D Model Calibration Results for November 1 to 2, 2000 Storm.....	72
Table 4 - 3. Boundary Inflow Hydrographs at Cross-sections 1-9.	77
Table 4 - 4. FLO-2D Model Result Summary for 10-year Flood Event.	86
Table 4 - 5. FLO-2D Model Result Summary for 50-year Flood Event.	87
Table 4 - 6. FLO-2D Model Result Summary for 100-year Flood Event.	88
Table 4 - 7. FLO-2D Model Result Summary for 500-year Flood Event.	89
Table A - 1. Rainfall for Each FLO-2D Model Sub-domain.	A-1
Table A - 2. Puna Study Area FLO-2D Results.	A-3



LIST OF ABBREVIATIONS

BFE	Base Flood Elevation
DLNR	Department of Land and Natural Resources, State of Hawaii
DPW	Department of Public Works, County of Hawaii
DTM	Digital Terrain Model
ESRI	"Environmental Systems Research Institute, Inc.
ft	feet
ft ²	Square Feet
FEMA	Federal Emergency Management Agency
FHM	Flood Hazard Map
GDS	Grid Developer System
GIS	Geographic Information Systems
HEC-GeoHMS	Hydrologic Engineering Center -Geospatial Hydrologic Modeling Extension
HEC-HMS	Hydrologic Engineering Center Hydrologic Modeling System
hr	hour
ID	Identification Number
IDF	Intensity-Duration-Frequency
in	inches
in/hr	Inches per hour
Ksat	Saturated Hydraulic Conductivity
LIDAR	Light Detection and Ranging
mi ²	Square Miles
min	minute
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
N-SPECT	Nonpoint-Source Pollution and Erosion Comparison Tool
OID	Operator Interface Device
Ref.	Reference
SID	Station Identifiers
SCS	Soil Conservation Service
T _c	Time of Concentration
TIN	Triangulated Irregular Network
T _t	Travel times
U.S.	United States
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
yr	year



EXECUTIVE SUMMARY

On November 1 to 2, 2000, a combination of several meteorological and topographic factors produced extreme rainfall over the eastern part of the Island of Hawai'i. Storm rainfall was concentrated in two distinct areas, the Puna and Kapāpala areas, where maximum rainfall totals of 32.47 and 38.97 inches were recorded (USGS 2000). Resultant flooding caused damages in excess of 70 million dollars, among the highest totals associated with flooding in the State's history. The department of Public Works (DPW), County of Hawai'i contracted Oceanit to perform the Puna Flood Study and generate Digital Flood Insurance Rates Maps (DFIRMs) for the Puna District, County of Hawai'i.

A hydrologic analysis was conducted using a hydrologic model to provide credible flood events in terms of the 10%, 2%, 1%, and 0.2% exceedance probabilities (i.e. the 10-, 50-, 100-, and 500-year return period floods) for the Puna District. The rainfall-runoff HEC-HMS (U.S. Army Corps of Engineers, Version 3.5) model was used in this analysis.

HEC-HMS is a lumped one-dimensional hydrologic model, which is a FEMA approved hydrology analysis model. Since no stream gage data are available for this study area, a two-dimensional hydrologic and hydraulic model- FLO-2D model was also developed to verify the result of the HEC-HMS model. Comparison of results between the two models helped to build the confidence in the simulation results in this area where no gage records are available.

The flood discharges calculated from the HEC-HMS hydrologic model were used as input for the subsequent hydraulic analyses. The results from the FLO-2D model were just used for comparison purpose only. Table ES-1 shows the peak discharges at nine selected junctions for storm events in terms of the different return periods. The two models provide similar and consistent results. Figure ES-1 provides watershed boundaries and junction locations for the Puna study area.

Using results of hydrology analysis for the Puna area, this study performed hydraulic analyses for flooding in the Puna area. FEMA's *Guidelines and Specifications for Flood Hazard Mapping Partners Appendix E: Guidance for Shallow Flooding Analyses and Mapping* is followed in the hydraulic analysis and mapping procedures. A two-dimensional analysis of the flood inundation at the Puna area was conducted using the FLO-2D flood routing model. This analysis simulated the 10-, 2-, 1-, and 0.2-percent-annual-chance events based on discharge hydrographs computed under the hydrologic analyses task.



Table ES-1. Peak Discharges for Storm Events.

Junctions	Description	10- Year (10% Annual Chance) cfs		50- Year (2% Annual Chance) cfs		100- Year (1% Annual Chance) cfs		500- Year (0.2% Annual Chance) cfs	
		HEC- HMS	FLO- 2D	HEC- HMS	FLO- 2D	HEC- HMS	FLO- 2D	HEC- HMS	FLO- 2D
J2	Volcano Rd & Kahaualeale Rd	9,454	9,596	23,955	22,330	35,157	33,418	46,240	46,266
J3	Near Mauaana Rd	19,063	17,648	40,749	36,532	59,984	54,024	80,339	74,770
J4	Near Apele Rd	19,538	17,410	36,533	31,291	45,384	44,008	61,031	63,610
J5	South Kūlani Rd Bridge	25,024	20,684	45,398	39,041	61,326	51,602	84,906	75,217
J7	Keaau-Pahoa Rd & Keaau Bypass Rd	15,187	14,734	30,993	31,463	40,720	40,507	63,826	59,910
J8	Volcano Rd & Huina Rd	5,859	6,017	12,212	13,046	17,055	16,191	25,270	24,023
J10	Railroad Aves. & Keaau Rd	1,361	1,248	3,916	3,684	5,539	5,640	11,894	11,935
JK1	Pulelehua Rd & Poola Rd	1,229	777	8,197	7,360	17,854	16,165	28,551	29,194
J16	Waimakao Pele Rd & Pahoehe Rd	241	171	1,035	1,080	2,672	2,608	8,712	8,581

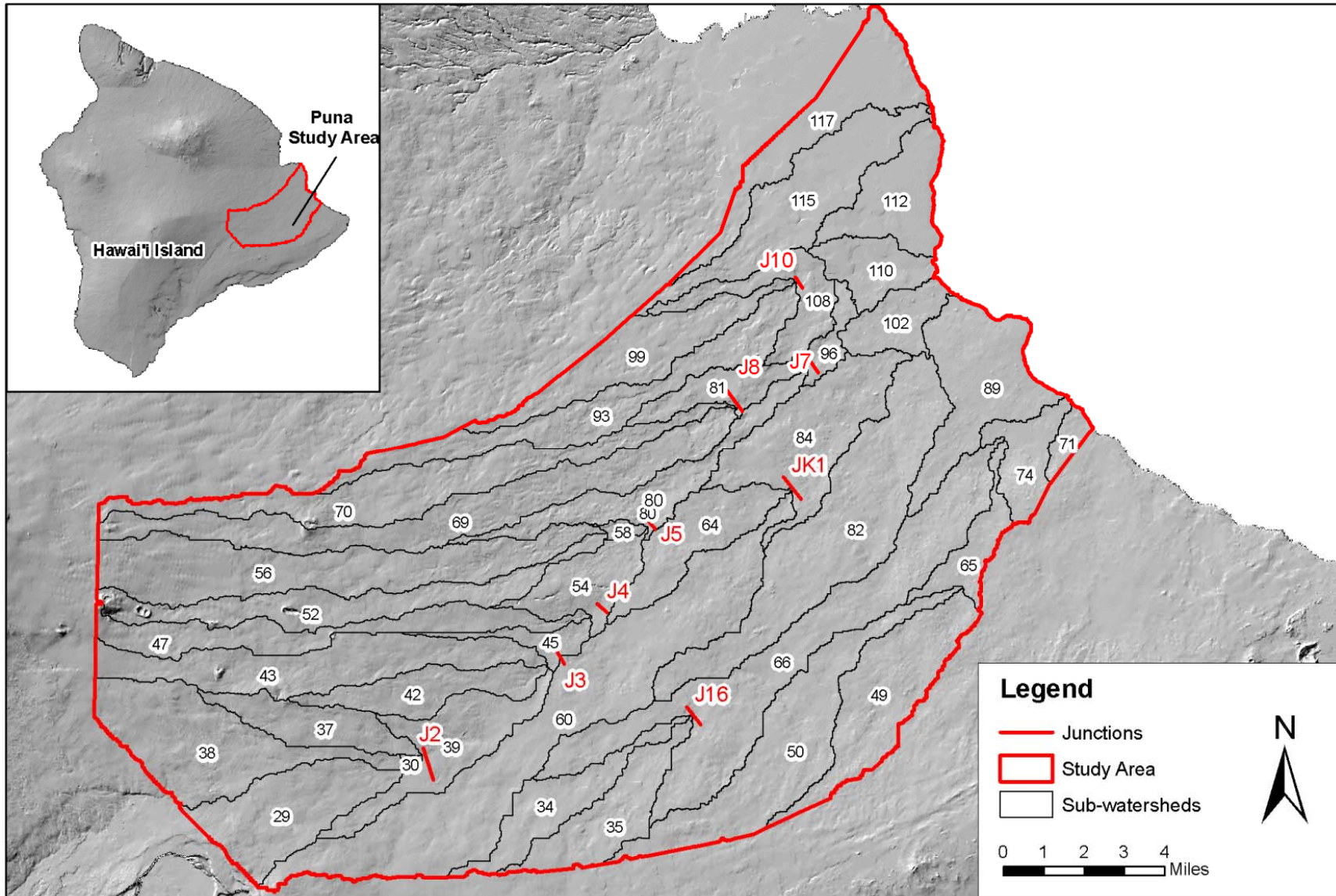


Figure ES-1. Watershed and Junction Locations.



1 INTRODUCTION

1.1 Background

The Puna area, located between the two volcanoes, Mauna Loa and Kilauea in the Island of Hawai'i, is formed by combined volcanic flows both from Mauna Loa and Kilauea. The altitude within the study area ranges from mean sea level at the coastal areas, to about 5,000 feet at the western boundary near the Mauna Loa Volcano. The entire study area is relatively flat with average slopes range between 2% to 6%. Since geologically this area is relatively young and drainage channelization is not well-developed, there is often flooding from unconfined flows. Flooding damage has mainly been caused by surface sheet flows. Historically, flash floods are very common at Puna area. The area indexed by Tax Map Key: 1-6, 7, 8 and 9 has had active storm events and substantial property damages in recent years.

On November 1 to 2, 2000, a combination of several meteorological and topographic factors produced extreme rainfall over the eastern side of Hawai'i Island. Storm rainfall was concentrated in two distinct areas, the Puna and Kapāpala areas, where maximum rainfall totals of 32.47 and 38.97 inches were recorded (USGS 2002). According to USGS (2002), this storm rainfall had recurrence intervals that were estimated from 25 years to 100 years for a 24-hour period. Major flooding occurred on the Waiakea and Palai Stream watersheds. The floodwater impacted the Hilo area causing Hawai'i County to evacuate over 200 people from their homes. Resultant flooding caused damages in excess of \$70 million, among the highest associated with flooding in the State's history.

A study of the hydrologic and hydraulic conditions in the area is essential to assess the flood hazard in the area and to determine the extent of administrative actions needed to safeguard life and property. In response to this event, the department of Public Works (DPW), County of Hawai'i has contracted Oceanit to perform hydrologic and hydraulic analyses and generate Digital Flood Insurance Rates Maps (DFIRMs) for the Puna district. This study focused on the flooding problem at the northern part of the Puna area, and is the first effort to generate the Digital Flood Insurance Rates Maps (DFIRM) for that part of Puna District, County of Hawaii.

1.2 Purpose and Scope

The Puna District currently does not have Flood Insurance Rate Maps (FIRMs). The purpose and scope of the Puna Flood Study is to conduct detailed hydrologic and hydraulic analyses in watershed and then produce reliable DFIRMs based on the results of these analyses. The Flood Hazard Maps (FHM) for the Puna Study area will delineate floodplain boundaries, providing a valuable planning reference for the county. This flood study investigates the severity of flood hazards in the northern area of the Puna District and provides a basis for the administration of the National Flood Insurance Act of 1968 and the Flood Disaster Protection Act of 1993. This study develops flood risk information that will be used to establish actual flood insurance rates and assist the community in its effort to promote sound floodplain management. Minimum floodplain management requirements for participation in the National Flood Insurance Program (NFIP) are set forth in the Code of



Federal Regulations (CFR) Title 44, Part 60.3. Coastal flooding analyses were not conducted as part of this study.

The report documents the hydrologic analyses of the Puna Flood Study Project. Hydrologic analysis determines the peak discharge-frequency relationships at junctions where flows from sub-watershed meet. Calculations were made for the northern Puna Study area in terms of peak flows for flood events that recur at 10-, 50-, 100-, and 500-year periods. These flood recurrence periods correlate to the exceedance probabilities of 10-, 2-, 1-, and 0.2-percent. These peak flood discharges were used as input for the subsequent hydraulic analyses.

The report describes the methodology and results of the FLO-2D hydraulic models. The hydraulic analyses based on numerical models were used to establish flood elevations and floodways for the project area. A two dimensional flood routing model FLO-2D was used to simulate flooding caused by 10-, 2-, 1-, and 0.2-percent-annual-chance events.

1.3 Methodology

A rainfall-runoff computer model (HEC-HMS Version 3.5) was utilized and is described in detail in Section 3. The HEC-HMS model for Puna study area is based on hypothetical meteorological events to simulate the rainfall in terms of varied return periods in a 24-hour duration. Precipitation frequency estimates from NOAA Atlas 14 (NOAA 2009) were used to determine the total cumulative rainfall produced by 10-, 50-, 100-, and 500-year frequency storms within the study area. As a lumped model, HEC-HMS applied the Green-Ampt method as its loss method and the Snyder unit hydrograph as its transform method. The HEC-HMS model for Puna study area used a historical storm event on November 1 and 2, 2000 as a calibration event. Four hypothetical meteorological events (10-, 50-, 100-, and 500-year frequency storms) were computed to obtain the flood discharges at varied return years. The flood discharges calculated from the HEC-HMS hydrologic model would be used as input for the subsequent hydraulic analyses in the hydraulic analysis report.

Due to the lack of stream gage data in the study area, FLO-2D (Version 2009) hydrologic model was also developed for the comparison purpose. FLO-2D is a distributed rainfall-runoff model, based on a volume conservation principle that distributes a flood hydrograph over a system of grid elements. The Green-Ampt loss method was applied to account for precipitation loss due to infiltration in the FLO-2D model. FLO-2D simulated the surface runoff by discretizing and solving flow continuity and momentum equations at the grid elements. FLO-2D model used the same storm rainfall data for its meteorological input as the HEC-HMS model. Comparison between the two types of the models helps to build confidence in the simulation results in this study area where no gage records are available. The results of the FLO-2D model were only used to verify the results of the HEC-HMS model.

The methodology used in the hydraulic analysis followed the FEMA's *Guidelines and Specifications for Flood Hazard Mapping Partners - Appendix E: Guidance for Shallow Flooding Analysis and Mapping*. A FEMA approved two-dimensional flood routing model FLO-2D was used to provide the flood elevations, regulatory floodways, and inundation areas. Topographic LiDAR data of the study area was used as the digital terrain data set for the



FLO-2D models. Additional topo data gaps was supplemented with field collected data. The FLO-2D models used steady state hydrographs from the hydrology analysis of this study to start the flood routing. The floodplain Manning's n values were assigned by referring the land use and land cover information of the Puna District. The entire watershed within the project area was split into five sub-domains. This provided more computational operable size for FLO-2D hydraulic modeling. Boundary conditions were generated to transfer flow hydrographs to downstream sub-domains. Total water volume conservation was tracked for each sub-model to ensure the accuracy of the FLO-2D models.

1.4 Previous Studies

The following reports and studies contain pertinent historical hydrologic information used for this study.

1. County of Hawai'i, Department of Planning. (October 1995). *Puna Community Development Plan*. Prepared by Community Management Associates, Inc.
2. County of Hawai'i, Department of Planning. (November 2005). *Puna Regional Circulation Plan, Final report*. Prepared by Townscape, Inc.
3. County of Hawai'i, Department of Public Works. (March 1974). *Mountain View Drainage Study and Master Plan*. Prepared by Austin, Smith & Associates, Inc.
4. County of Hawai'i, Department of Public Works. (August 1976). *Mountain View Drainage Improvements, Environmental Impact Statement*.

1.5 Acknowledgements

Many thanks to the project managers of the County of Hawai'i, Department of Public Works, Mr. Frank DeMarco and Mr. Carter Romero for constructive advice and support on this project. Mahalo to Highway Maintenance Division for helping find historical flooding locations and identifying the approximate floodwater depths of historical flooding events.



2 STUDY AREA DESCRIPTION

2.1 Study Area Overview

Puna is one of nine districts in Hawai'i County and is located on the east side (windward side) of the Island of Hawai'i, sharing borders with the South Hilo District to the north and Ka'u District to the west. The Puna District encompasses 499.5 square miles or 319,680 acres. Primary access to the district is from the east-west roadway (Volcano Road) that runs parallel to the northern boundary of the district. A main branch road at Kea'au runs south to access the southern and eastern portions of the district.

The Puna study area is shown in Figure 2 -1. The figure also includes areas from Tax Map Key maps 1-6, 7, 8, & 9, which in recent years has experienced both active land development and storm events capable of substantial property damage. The study area for the project includes the northernmost portion of the Puna District and lies below 5000-foot elevation. The study area is approximately 282 square miles (mi²), or 180,480 acres, including the subdivisions of Mountain View, Kurtistown, Kea'au, Hawai'i Acres, Orchid Land, Hawaiian Paradise Park, and Fern Forest.

2.2 Topography, Vegetation, and Land Use

A large fraction of the Puna study area in Puna is characterized by gently sloping topography with poorly defined waterways. The Puna landscape is formed of porous volcanic rock and soils from Mauna Loa and Kilauea volcanic eruptions. An extensive network of subterranean lava tubes runs throughout much of the study area and are accessible through collapsed openings (Facts about Puna Hawai'i 2012).

Vegetation in the study area varies from rain forest to desert shrub and coastal strand. The historic landscape of Puna was covered with forest, brush, and coastal strand prior to being transformed into ranchland and sugarcane fields (County of Hawai'i, Department of Planning 2005). Between historic lava flows, Puna vegetation started with lichens, ferns, and shrubs. Historically, this region supported wet and dry taro, banana, sugarcane, sweet potato, coconut, and breadfruit (Rhodes 2001).

Puna watershed land use is generally zoned as agricultural, residential, open (conservation), industrial, or commercial (County of Hawai'i, Department of Planning 2005). Actual land uses include residential subdivisions, agricultural farms, an industrial park, and several small commercial service centers.

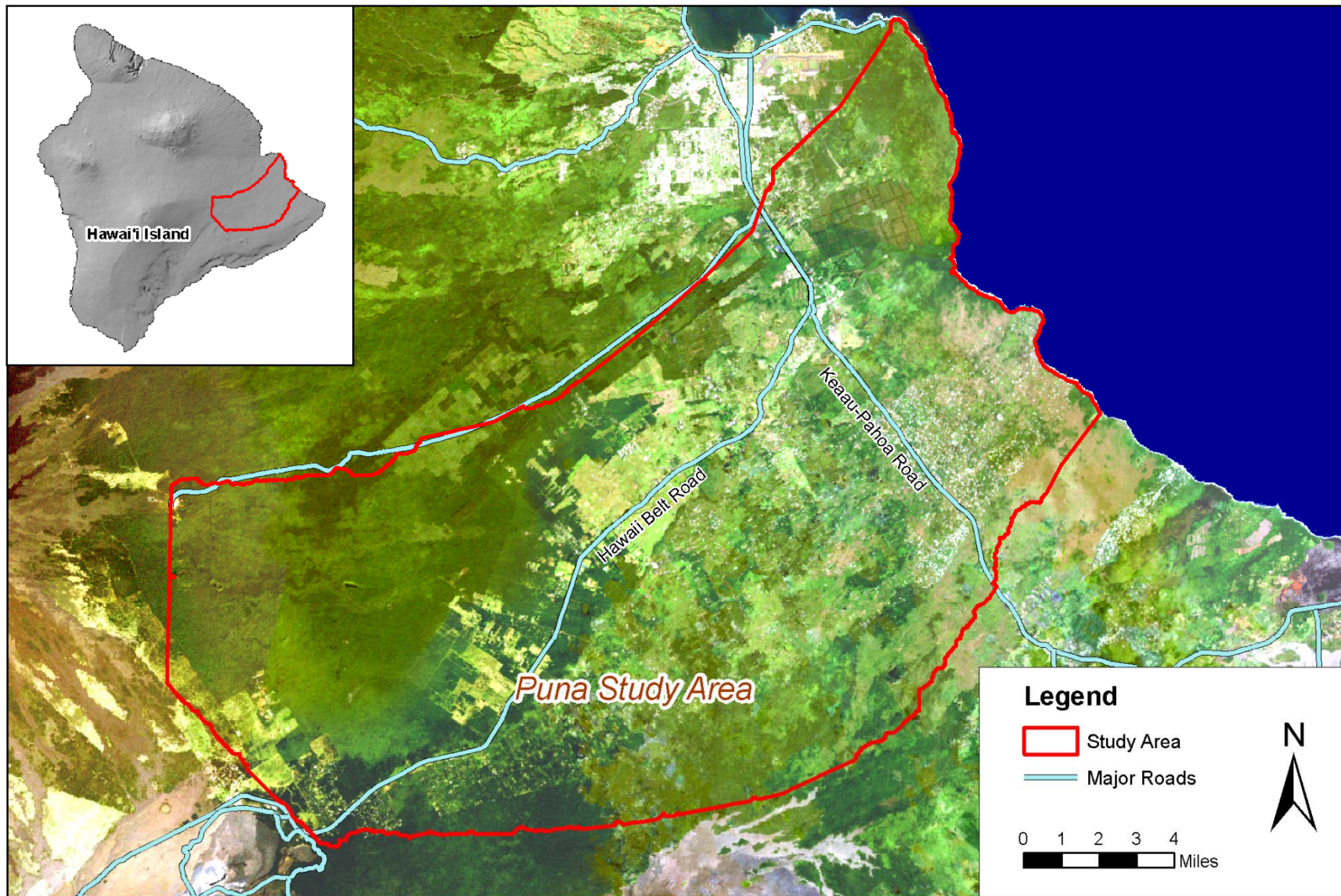


Figure 2 - 1. Location Map for Puna Study Area.



2.2.1 Geology and Climate

The Puna region was formed as part of the shield volcano mountain-building process of Mauna Loa and Kīlauea. Kīlauea is currently active and lava has covered numerous acres of developed lands within the Puna District in the last thirty years. Recent eruptions have generally been limited to National Park lands (County of Hawai'i, Department of Planning 2005). The lava tubes and cave systems of the Puna area are an integral and common element of extrusive volcanic landscapes in shield volcanoes such as Kīlauea and Mauna Loa. Although exact numbers cannot be determined, thousands of lava tubes possibly lie within the pāhoehoe lava flows, and most of these caves are too small to be an important concern in land planning.

The Puna flood study area is located between two volcanoes, Mauna Loa and Kīlauea, and formed by lava flows both from Mauna Loa and Kīlauea. The rocks of Kīlauea are divided into the older Hilina Volcanic Series and the younger Puna Volcanic Series. The Puna Series overlies Pāhala ash and is correlative with the Ka'u Series of Mauna Loa. Lava flows of the Puna and Ka'u series interfinger along the boundary between the two volcanoes. Both the Hilina and the Puna Series consist of pāhoehoe and 'a'ā lava flows of tholeiitic basalt, olivine basalt, and oceanite, and associated cinder-and-spatter cones and ash deposits (MacDonald 1983).

The lavas of the Puna Volcanic Series erupted almost entirely from vents in the area of the present Kīlauea caldera and along two rift zones that extend in an east west direction from the summit of the volcano (Wright and Fiske 1971). At the top of the Hilina fault scarp, lavas are only one or two flows thick, but in the cliff at western side of the caldera lava flows totaling 380 feet thick are exposed. The total thickness of Puna lavas is only a slight bit more than the thickness now visible in the cliff. Elsewhere, their base is not exposed, and the thickness is unknown (Wright and Fiske 1971).

The altitude within the study area ranges from mean sea level along the coastal areas to 1,950 feet at Mountain View and approximately 4,950 feet at the western boundary on the slope of Mauna Loa. The entire study area is relatively flat with the average slope ranging between 2% to 6% (Facts about Puna Hawai'i 2012).

Several soil groups are found in the Puna study area. Although all the surface geologic materials are highly permeable, the different permeabilities of 'a'ā lava flows, pāhoehoe lava flows, and ash are likely to affect infiltration and runoff during rainfall. Stearns and Macdonald (1946) considered the Pāhala Ash to be generally less permeable than the lava flows of the Hamakua Volcanics, and suggested that the ash may increase runoff during storms. Sato et al. (1973) considered pāhoehoe lavas to have low permeability in comparison to surrounding soils, although they noted that 'a'ā lava flows act as ground-water recharge areas presumably contributing little or no surface runoff. For most soils (Sato et al. 1973), surface permeability varies from 2.0 to 4.0 in/hr. The permeability of most soils overlaying ash or pāhoehoe lavas, at depths range from 8 to 72 inches below the land surface, has a decrease about two orders of magnitude. The parts of the study area are more likely to generate shallow subsurface flow during heavy rainfall, owing to their decrease in permeability at shallow depths on steep slopes (Freeze 1974).



The climate in Puna varies widely due to significant changes in elevation. The study area stretches from sea level up to about 5,000 feet elevation. The climate in the study area is tropical with large fluctuations in temperature and rainfall depending on location and elevation. Temperatures average 67 degrees Fahrenheit (°F) in Mountain View at the 1,530-foot elevation and daily temperatures range between 50 and 68 degrees. August and September are the warmest months, January, February, and March are the coolest (Puna Weather 2012). Rainfall averages 132 inches per year (Druecher and Fan 1976). June is usually the driest month, and December is the wettest. However, monthly and annual rainfalls are very unpredictable, and rainfall in East Hawai'i can vary by a factor of three from year to year (60 to 180 inches a year) (Puna Weather 2012). Rainfall averages are higher at upper elevations and range from 50 inches a year along the southwestern coast to 300 inches in the northern boundary of the Puna District (County of Hawai'i, Department of Planning 2005).

2.2.2 Water Resources and Hydrology

Puna's major potable water source comes from rainwater catchment. County water is available in some areas, usually located close to the highways. Puna's abundant rainfall and the absence of sediment load create high-quality groundwater (Facts about Puna Hawai'i 2012).

High rainfall, particularly in the upper elevations, contributes to the abundant water resources that can be found throughout the area (Facts about Puna Hawai'i 2012). Due to the high permeability of the rocks and soils, there are no well-defined perennial streams in the study area (Oki 2003).

2.3 Hydrologic Data

The character of the land, historical rainfall data, and historical stream flow data are relevant to the hydrological analysis of the Puna study area. Data used for analysis included rainfall gage data, records of historical storm events, and field surveys. Stream flow gage data are not available in this region. Rainfall intensity-frequency-duration (IDF) relationships were determined from this raw data. The rainfall data is used for meteorological input in the hydrological rainfall-runoff models discussed in Section 3.

2.3.1 Rain Gages

Critical rainfall data, obtained for this study from gages throughout the Puna study area, was used for hydrological analysis purposes. According to the State Geographic Information Systems (GIS) program (<http://www.state.hi.us/dbedt/gis/>), up to 30 rain gages are in the study area, however only a few of them are currently active. In total, five gages owned by the National Weather Service were used for calibration of the hydrologic analysis. Rain gages with available historical precipitation data for the storm on November 1 and 2, 2000, are:



- Gage HI81, Mountain View
- Gage HI-83 Pāhoa Rain Gage
- Gage HI-91 Piihonua Rain Gage
- Gage HI-92 Waiākea Uka Rain Gage
- Gage HI-94 Glenwood Rain gage

Table 2-1 and Figure 2-2 provide the names, locations, elevations, and identification numbers for these rain gages. These rainfall gages record either daily total measurements or real-time measurements at 15-minute time intervals.

Table 2 - 1. Rain Gages.

	SID	OID	LATITUDE	LONGITUDE	ELEVATION (feet)
Glenwood	GLNH1	HI-94	19.508N	-155.171W	2,632
Mountain View	MTVH1	HI-81	19.549N	-155.110W	1,519
Pahoa	PHAH1	HI-83	19.541N	-154.973W	487
Piihonua	PIIH1	HI-91	19.710N	-155.139W	974
Waiakea Uka	WKAH1	HI-92	19.659N	-155.128W	997

2.3.2 Stream Gages

There are no stream gages located in the study area.

2.3.3 Field Survey

Field surveys were conducted by Oceanit to locate and verify stream conditions that may lead to flooding. Locations and sizes of the drainage pipes were noted for drainage analysis purposes. Field surveys verified drainage inlet points, possible constriction points, overflow points, and a flood diversion structure near South Kūlani Road. Hydraulic structures were also measured for the subsequent hydraulic analysis.

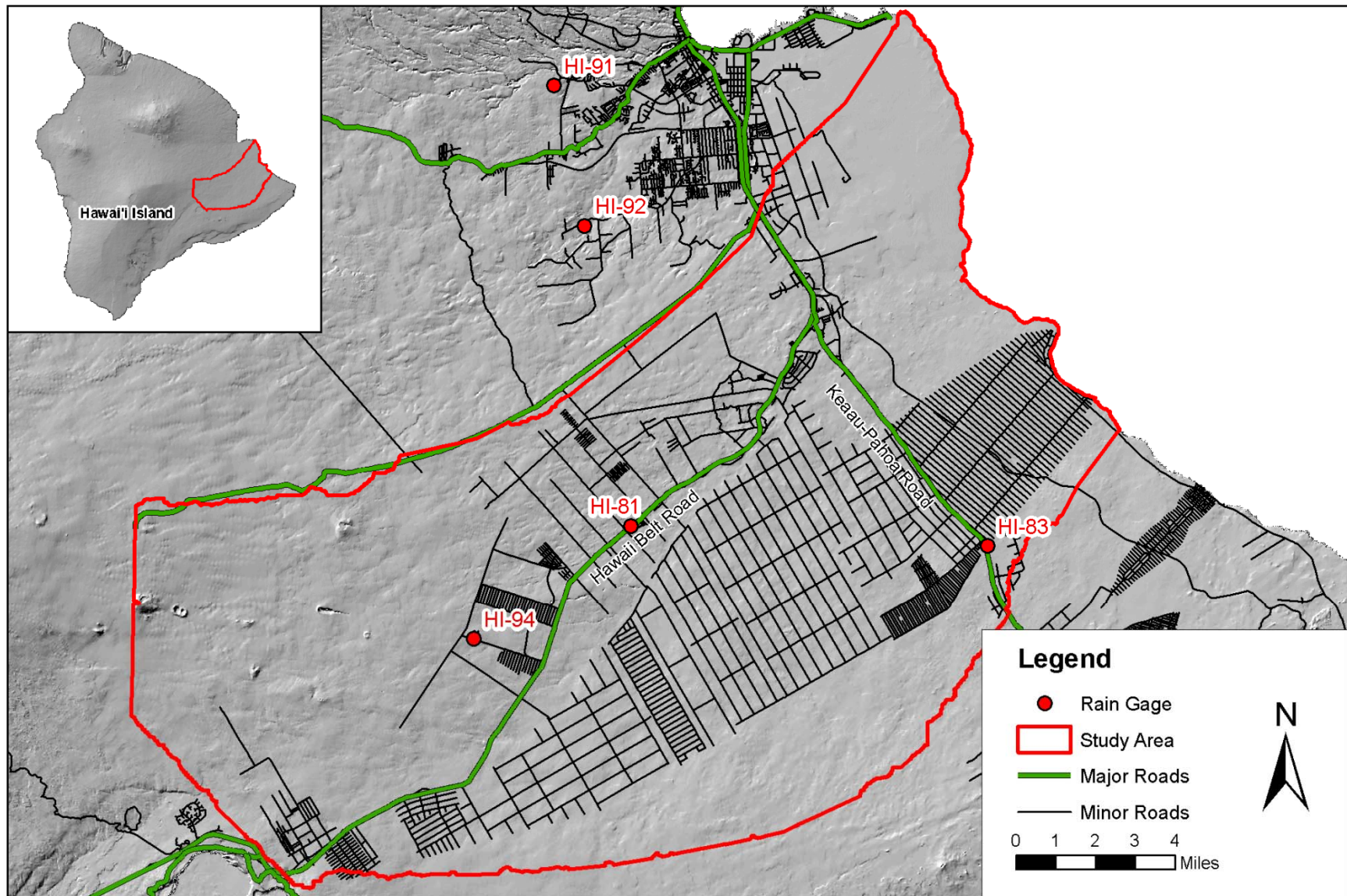


Figure 2 – 2. Rain Gages for Puna Study.



2.4 Flooding Problems in the Study Area

Information in the Puna Community Development Plan (County of Hawai'i 1995) identified subdivisions in Glenwood on the Mauna Loa side of Highway 11 (Hawaii Belt Road) including Orchid Isle, Aloha, Glenwood, and Pacific Paradise Mountain View Manor are areas that are particularly subject to flooding, because of high rainfall and low permeability ash clay soil. Roads have incurred flooding damage repeatedly. The cost for drainage improvements, to mitigate flooding for permitted development, is expected to be prohibitive (County of Hawai'i 1995). The most severe flooding event in the Puna study area occurred during November 1 and 2, 2000. Prolonged and intensive rain fell in two separate areas of the Hawaii Island: the Waiakea area and the Kapāpala area.

The Puna flood study area, which extends from about Pāpa'ikou on the north to Glenwood on the south and from sea level to the altitude of approximately 4,000 ft, is located in the Waiākea High-rainfall area (USGS 2002). Because of the high rainfall and ash clay soil, the subdivisions in Glenwood on the Mauna Loa side of Highway 11 including Orchid Isle, Aloha, Glenwood, and Pacific Paradise Mountain View Manor are particularly subject to flooding (County of Hawai'i, Department of Public Works 1976). Roads have been washed out repeatedly. There is no clearly defined drainage ways within the study area (County of Hawai'i, Department of Public Works 1974).

2.5 South Kūlani Flood Diversion Structure

The South Kūlani Flood Diversion Structure is a V-shape flow split dike with a series of guiding walls, totaling over one half mile in length. This structure channels water into Hawaiian Acres starting at the South Kūlani Road Bridge. The depth of water along the structure, in Hawaiian Acres and Orchid Isle areas, can exceed five feet during heavy rainfall events. According to the residents, the structure was built by 'Ōla'a Sugar Company in 1938 to divert floodwater away from sugar cane fields along the Mauna Loa/Kīlauea boundary into what was then called "wasteland" owned by W.H. Shipman (Puna Community Development Plan 1995). The structure consisted of a cemented stone wall, which crosses five lots in Hawaii Acres. The wall is overgrown with strawberry, guava, and other plants. Portions of the wall are significantly damaged because of tree roots and lack of maintenance. In 1979, debris blocked the flow under South Kūlani Bridge, diverting floodwaters away from the wall to what may have been the original drainage channel (Puna Community Development Plan 1995).



3 HYDROLOGIC ANALYSIS

3.1 HEC-HMS Model Overview

The U.S. Army Corps Hydrologic Modeling System (HEC-HMS) is designed to simulate the precipitation-runoff processes of dendritic watershed systems. This model is a one dimensional precipitation-runoff process model which includes a basin model, a meteorological model, and a control model.

Covering the project watershed area, a basin model was built based on the sub-watershed delineations. In this study, the final basin model consisted of 39 sub-watersheds. Key parameters of the basin model were based on acceptable methodologies of hydrologic analysis. The Green-Ampt infiltration method was used as the loss method, and the Snyder Unit Hydrograph method was the transform method used for creating peak discharges and relevant hydrographs. The NRCS TR-55 model was used to determine the parameters for the time of concentration (T_c). Channel routing through reaches was done by the Kinematic Wave method to account for peak flow attenuation. A total of 20 stream reaches were modeled using the Kinematic Wave routing method to simulate open channel flow within the simulated stream channels and their banks. The parameters of length, slope, and shape for each reach were determined based upon topographic data, field survey, and satellite imagery. The Manning's n values for stream channel and its banks were determined using Chow's (1959) guidelines and actual channel conditions.

The meteorological model used historical storm hydrographs for calibration and frequency-based rainfall to compute the synthetic flood events. For creating the peak discharges of varied return periods, the frequency storm with an intensity position at the 50% time period was used in computing the peaks and hydrographs.

The control model set the computation parameters such as starting time, ending time, and time interval. This model used a 15-minute computation interval for calibration and a 5-minute interval for frequency storm computations.

3.2 Geospatial Information Used

Geospatial information and field survey observations were used to determine the hydrological conditions, such as the terrain roughness characteristics and the stream channel cross-section shapes. Information collected includes LiDAR data and aerial maps.

LiDAR data was used as original input using ArcView 3.3 with the HEC-GeoHMS 1.1 extension to create a geospatial model of the Puna watershed. The HEC-GeoHMS model was the tool to delineate the initial sub-watershed boundaries, calculate sub-watershed areas, and to determine flow path lengths and slopes. NOAA's Nonpoint Source Pollution and Erosion Comparison Tool (N-SPECT) was also used to delineate the watershed. N-SPECT is an extension to Environmental Systems Research Institute's (ESRI) ArcGIS software package, version 9.x, and requires ESRI's Spatial Analyst extension. N-SPECT is designed to provide the user access to the necessary data. The final sub-watershed delineation was a combination of results of HEC-GeoHMS and the N-SPECT models. Figure 3-1 shows the



delineated sub-watersheds of the Puna study area. The centroids of each sub-watershed are shown in Figure 3-2. The sub-watersheds, their areas, and their centroids are listed in Table 3-1.

After the sub-watersheds were delineated, the layout and structure of the HEC-HMS model were developed. Figure 3-3 shows the HEC-HMS model layout. The letter “J” refers to junctions in the model and the letter “R” refers to reaches in the model. Figure 3-4 displays the same HEC-HMS model layout but rearranges the sub-watershed positions for a clearer illustration of the model structure. A total of 23 junctions are in the HEC-HMS model. These junctions are listed in Table 3-2, which also shows the sub-watersheds and associated drainage areas for each junction. Nine major junctions were selected to summarize the peak discharges of the HEC-HMS model and also used to compare the peak discharges of the HEC-HMS model with the results of another hydrologic model (FLO-2D model). These nine junctions of interest are shown in Figure 3-5.

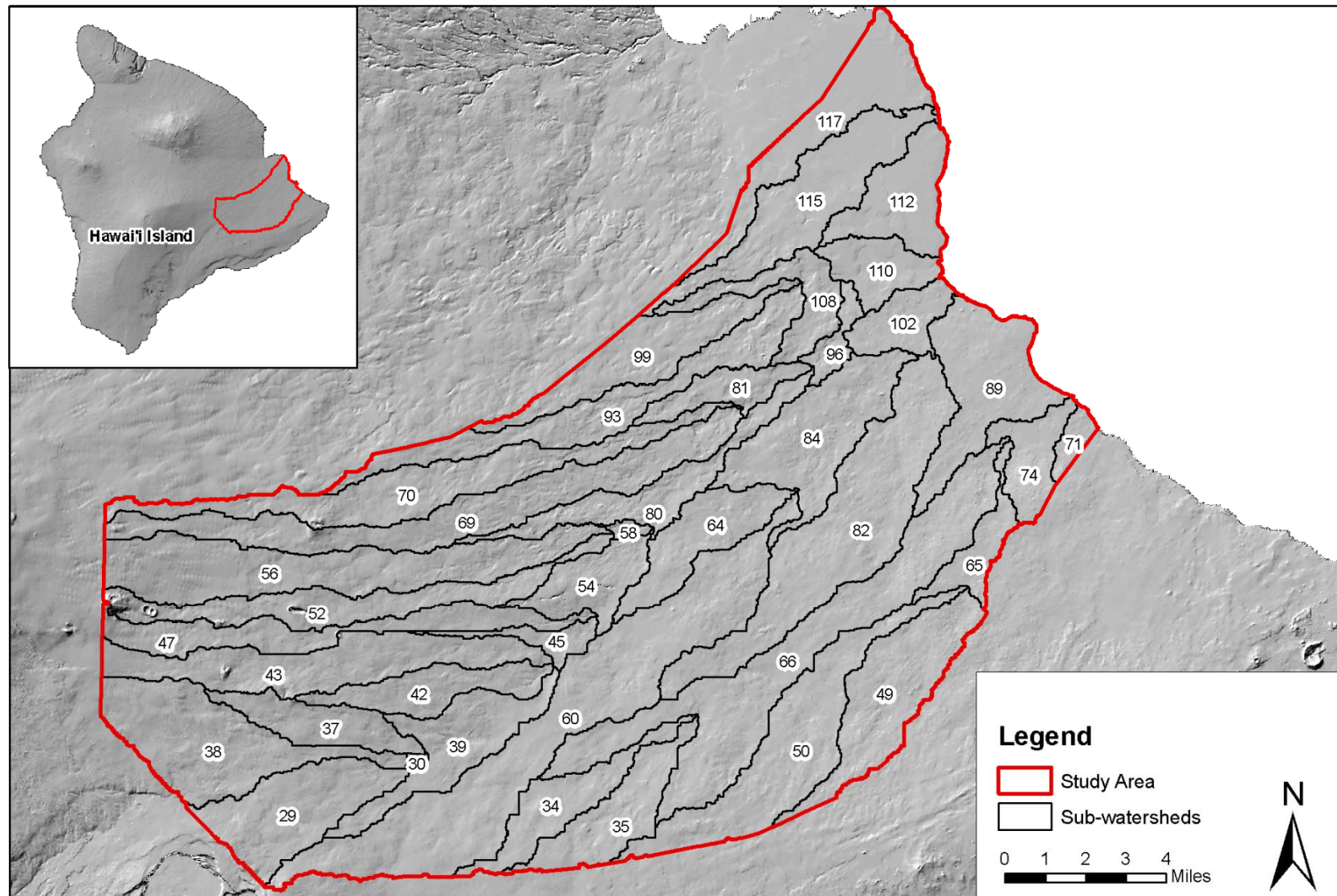


Figure 3 - 1. Puna Study Sub-watershed.

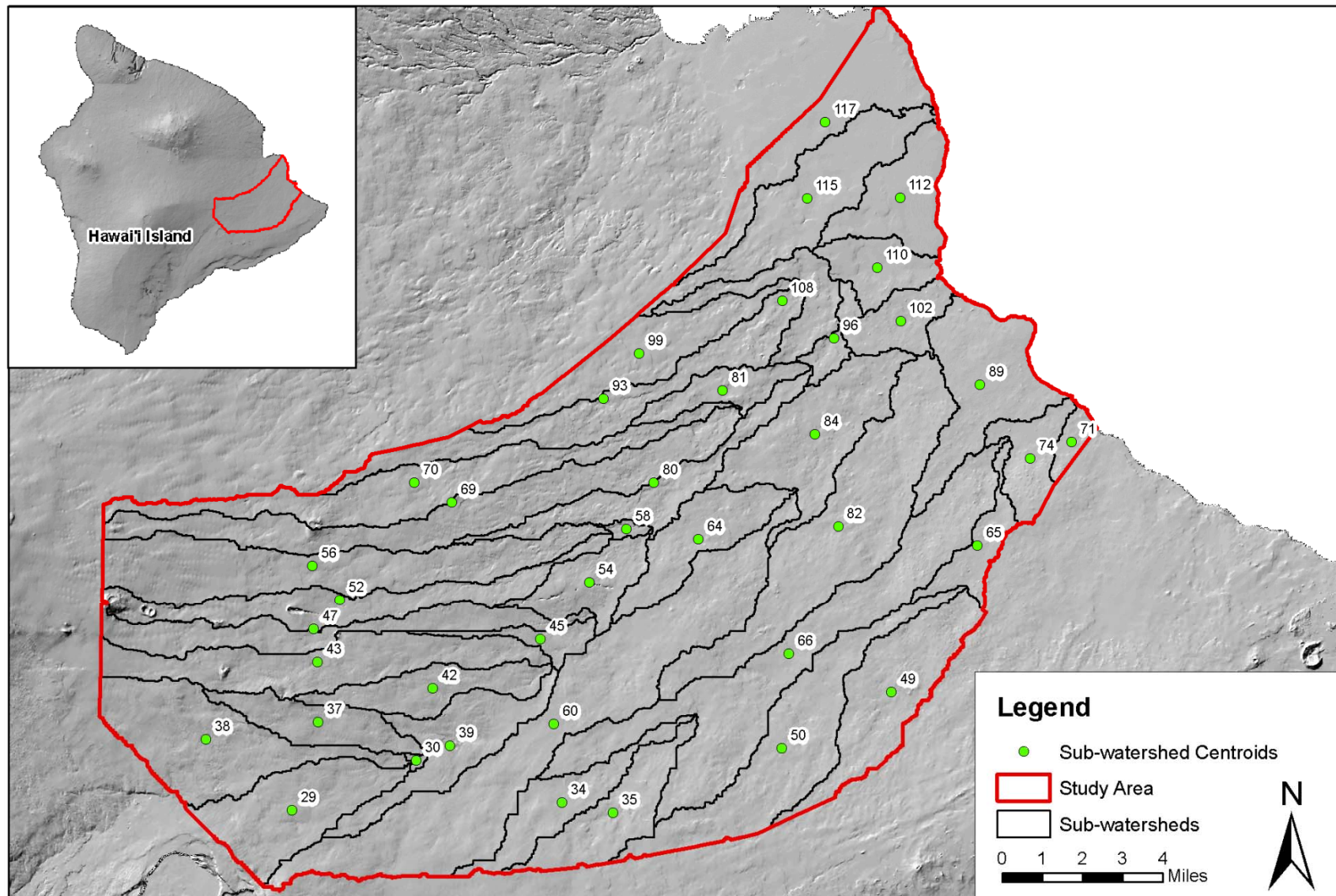


Figure 3 - 2. Sub-basin Centroids for Puna.

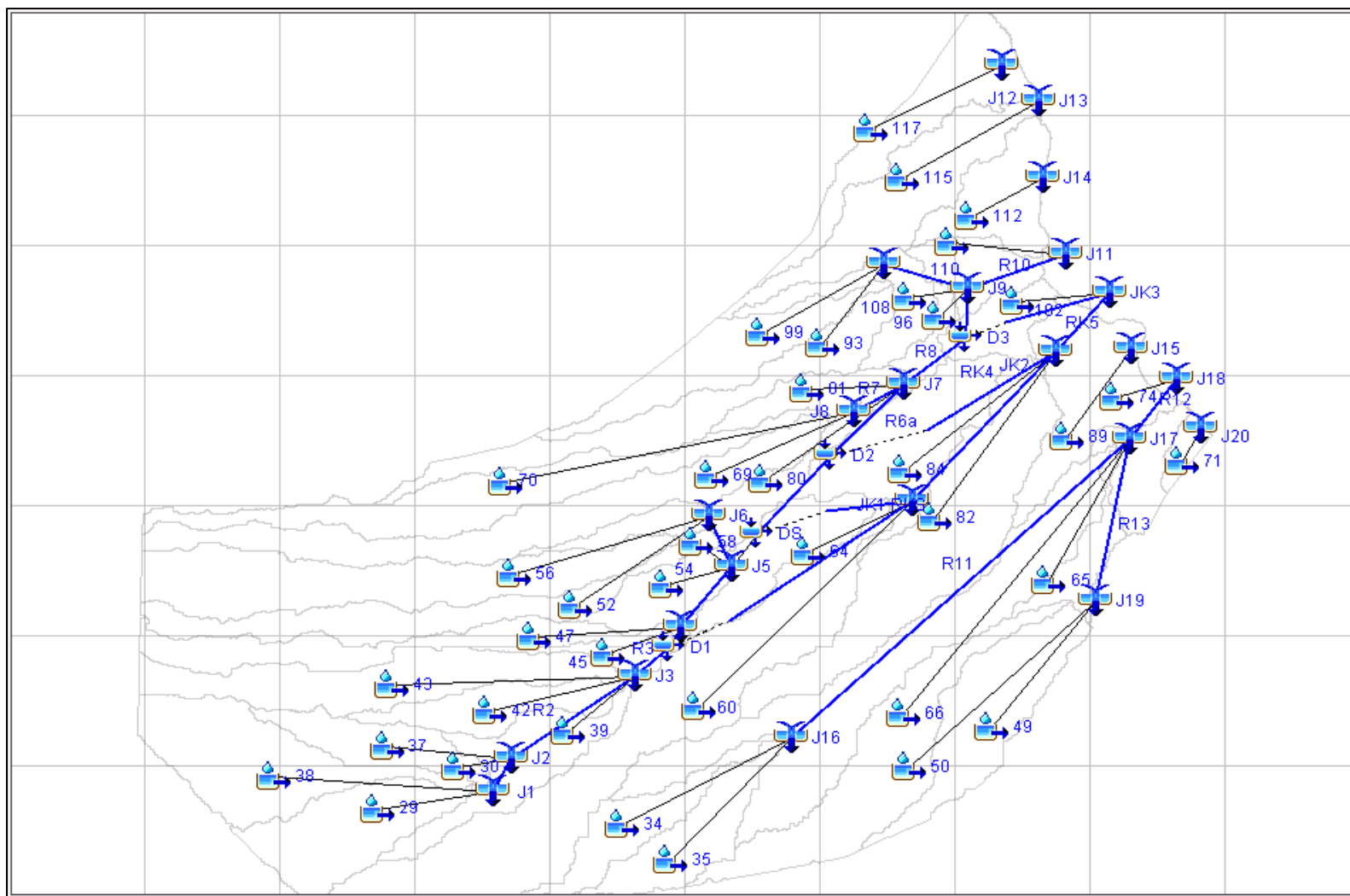


Figure 3 - 3. HEC-HMS Model Layout for Puna Study Area.

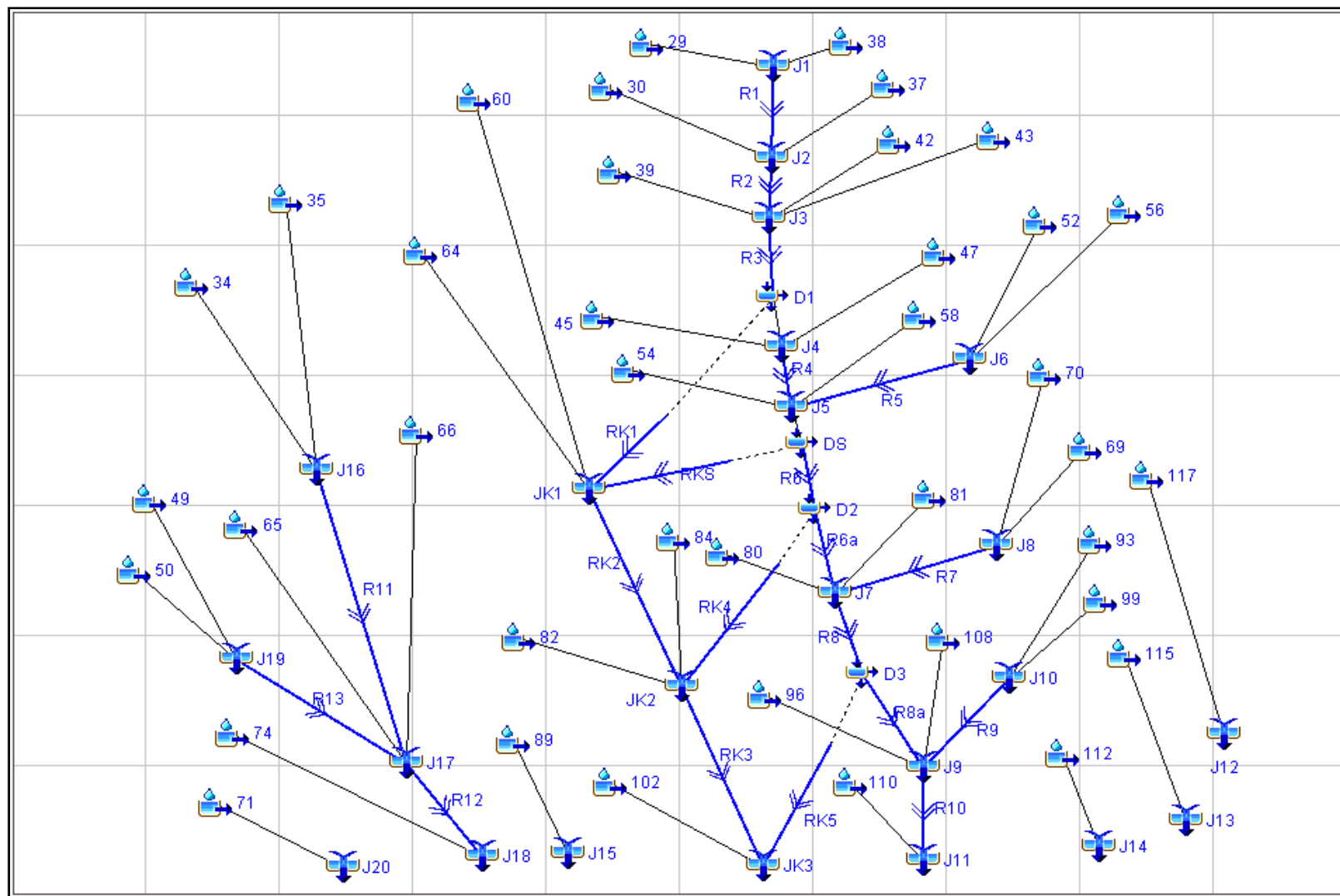


Figure 3 - 4. HEC-HMS Model Structure for Puna Study Area.

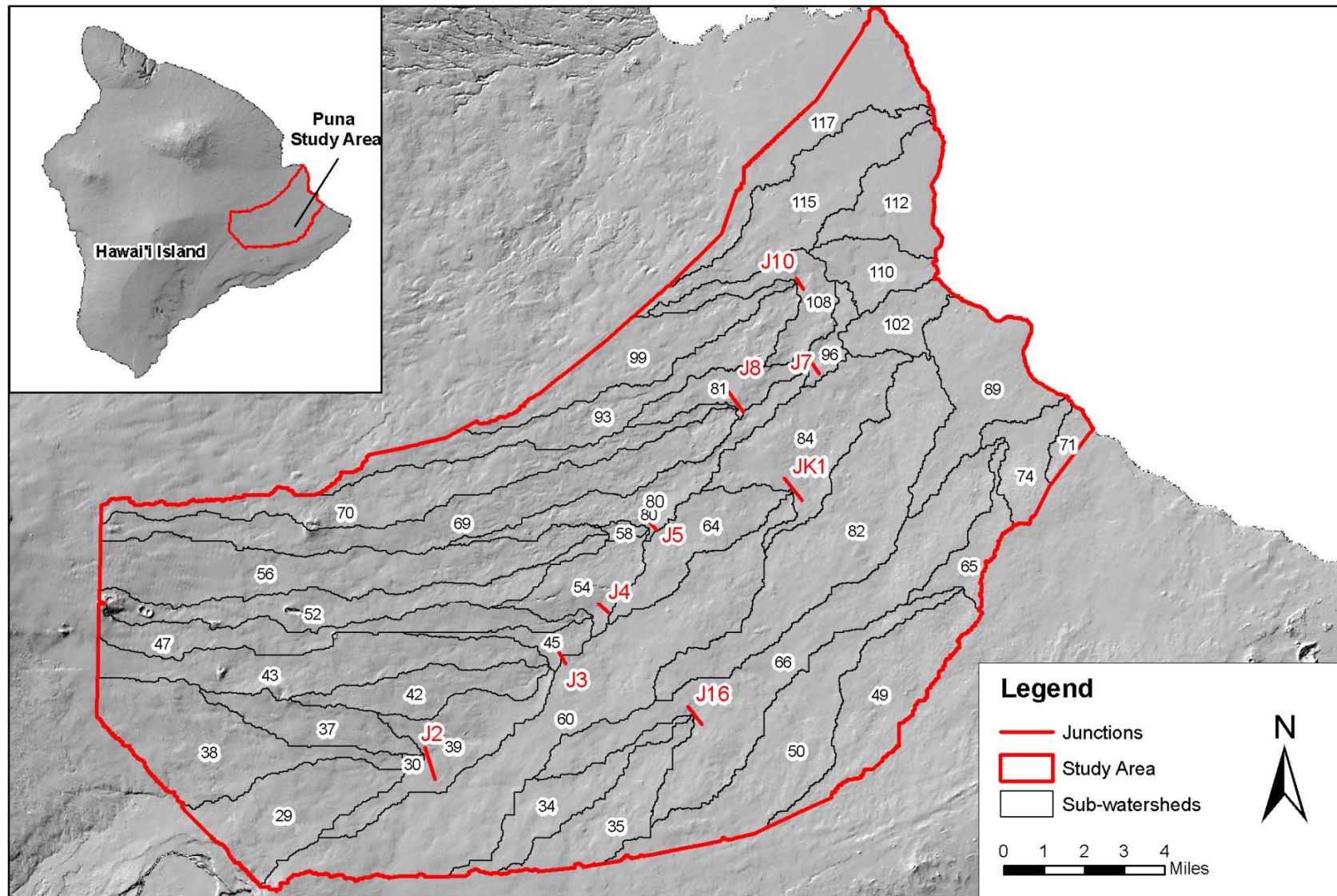


Figure 3 - 5. Junctions of Interest for Puna Study Area.



Table 3 - 1. Sub-Watersheds, Areas and Centroids.

Sub-Watershed	Area (mi ²)	Centroid Point	
		Longitude	Latitude
29	7.982	-155.229W	19.446N
30	0.156	-155.182W	19.464N
34	4.676	-155.126W	19.448N
35	5.462	-155.107W	19.445N
37	4.188	-155.219W	19.478N
38	10.575	-155.262W	19.471N
39	6.322	-155.169W	19.469N
42	4.47	-155.134W	19.507N
43	9.968	-155.175W	19.490N
45	1.643	-155.219W	19.499N
47	6.909	-155.221W	19.511N
49	8.748	-155.001W	19.488N
50	11.267	-155.042W	19.468N
52	7.673	-155.211W	19.522N
54	4.147	-155.115W	19.528N
56	13.594	-155.221W	19.534N
58	0.378	-155.101W	19.547N
60	22.874	-155.129W	19.477N
64	5.449	-155.074W	19.544N
65	2.753	-154.968W	19.541N
66	17.86	-155.040W	19.502N
69	12.826	-155.168W	19.557N
70	10.425	-155.182W	19.564N
71	1.147	-154.931W	19.579N
74	3.414	-154.947W	19.573N
80	5.492	-155.091W	19.564N
81	2.883	-155.065W	19.598N
82	16.042	-155.021W	19.548N
84	9.195	-155.029W	19.582N



Puna Flood Study
Hydrologic and Hydraulic Report

Sub-Watershed	Area (mi ²)	Centroid Point	
		Longitude	Latitude
89	8.656	-154.966W	19.599N
93	8.862	-155.110W	19.595N
96	1.456	-155.022W	19.616N
99	7.239	-155.096W	19.611N
102	3.132	-154.996W	19.623N
108	3.979	-155.042W	19.630N
110	3.428	-155.005W	19.642N
112	5.449	-154.997W	19.667N
115	9.23	-155.032W	19.667N
117	8.502	-155.025W	19.695N



Table 3 - 2. Sub-watersheds, Junctions, and Drainage Areas of Puna Study Area.

Sub-watershed/Junction	ID	Drainage Area (mi ²)
<i>Middle Sub-domain</i>		
Subwatershed 29	29	7.871
Subwatershed 38	38	10.500
Junction 1	J1	18.370
Subwatershed 30	30	0.156
Subwatershed 37	37	4.188
Junction 2	J2	22.714
Subwatershed 39	39	6.351
Subwatershed 42	42	4.491
Subwatershed 43	43	9.906
Junction 3	J3	43.462
Subwatershed 45	45	1.593
Subwatershed 47	47	6.857
Junction 4	J4	51.912
Subwatershed 52	52	7.644
Subwatershed 56	56	13.473
Junction 6	J6	21.117
Subwatershed 54	54	4.147
Subwatershed 58	58	0.378
Junction 5	J5	77.554
Subwatershed 69	69	12.785
Subwatershed 70	70	10.367
Junction 8	J8	23.151
Subwatershed 80	80	5.492
Subwatershed 81	81	2.883
Junction 7	J7	109.080



Sub-watershed/Junction	ID	Drainage Area (mi ²)
Subwatershed 93	93	8.722
Subwatershed 99	99	6.941
Junction 10	J10	15.663
Subwatershed 96	96	1.456
Subwatershed 108	108	3.979
Junction 9	J9	130.179
Subwatershed 110	110	3.429
Junction 11	J11	133.607
Subwatershed 60	60	22.792
Subwatershed 64	64	5.449
Junction K1	JK1	28.241
Subwatershed 82	82	16.042
Subwatershed 84	84	9.195
Junction K2	JK2	53.478
Subwatershed 102	102	3.131
Junction K3	JK3	56.609
<i>South Sub-domain</i>		
Subwatershed 34	34	4.660
Subwatershed 35	35	5.419
Junction 16	J16	10.079
Subwatershed 49	49	8.644
Subwatershed 50	50	11.160
Junction 19	J19	19.804
Subwatershed 65	65	2.753
Subwatershed 66	66	17.860
Junction 17	J17	50.497
Subwatershed 74	74	3.352



Junction 18	J18	53.849
Sub-watershed/Junction	ID	Drainage Area (mi²)
Subwatershed 71	71	1.037
Junction 20	J20	1.037
Subwatershed 89	89	8.660
Junction 15	J15	8.660
<i>North Sub-domain</i>		
Subwatershed 112	112	5.466
Junction 14	J14	5.466
Subwatershed 115	115	9.147
Junction 13	J13	9.147
Subwatershed 117	117	7.622
Junction 12	J12	7.622

3.3 Meteorological Events

The Puna HEC-HMS model is based on hypothetical meteorological events to simulate the rainfall in terms of varied return periods in a 24-hour duration. Precipitation frequency estimates from NOAA Atlas 14 (NOAA 2009) were used to determine the total cumulative rainfall produced by 10-, 50-, 100-, and 500-year frequency storms in the study area. Atlas 14 contains precipitation frequency estimates for the United States and U.S. affiliated territories (Perica, et al. 2009). The precipitation in the centroid of a particular sub-watershed was applied to the entire sub-watershed uniformly. The precipitation values used for the 10-, 50-, 100-, and 500-year return storm events in a 24-hour were plotted in Figures 3-6 through 3-9. The number in each sub-watershed is the rainfall value that was used. The Rainfall values that were extracted from Atlas 14 for various storm return periods and durations for each sub-watershed are listed in Table 3-3.

With the IDF for each sub-watershed available (Table 3-3), hyetographs were generated using the HEC-HMS frequency storm method with an intensity position at 50%. Figure 3-10 shows a typical 24-hour, 100-year accumulated hyetograph for a sub-watershed.

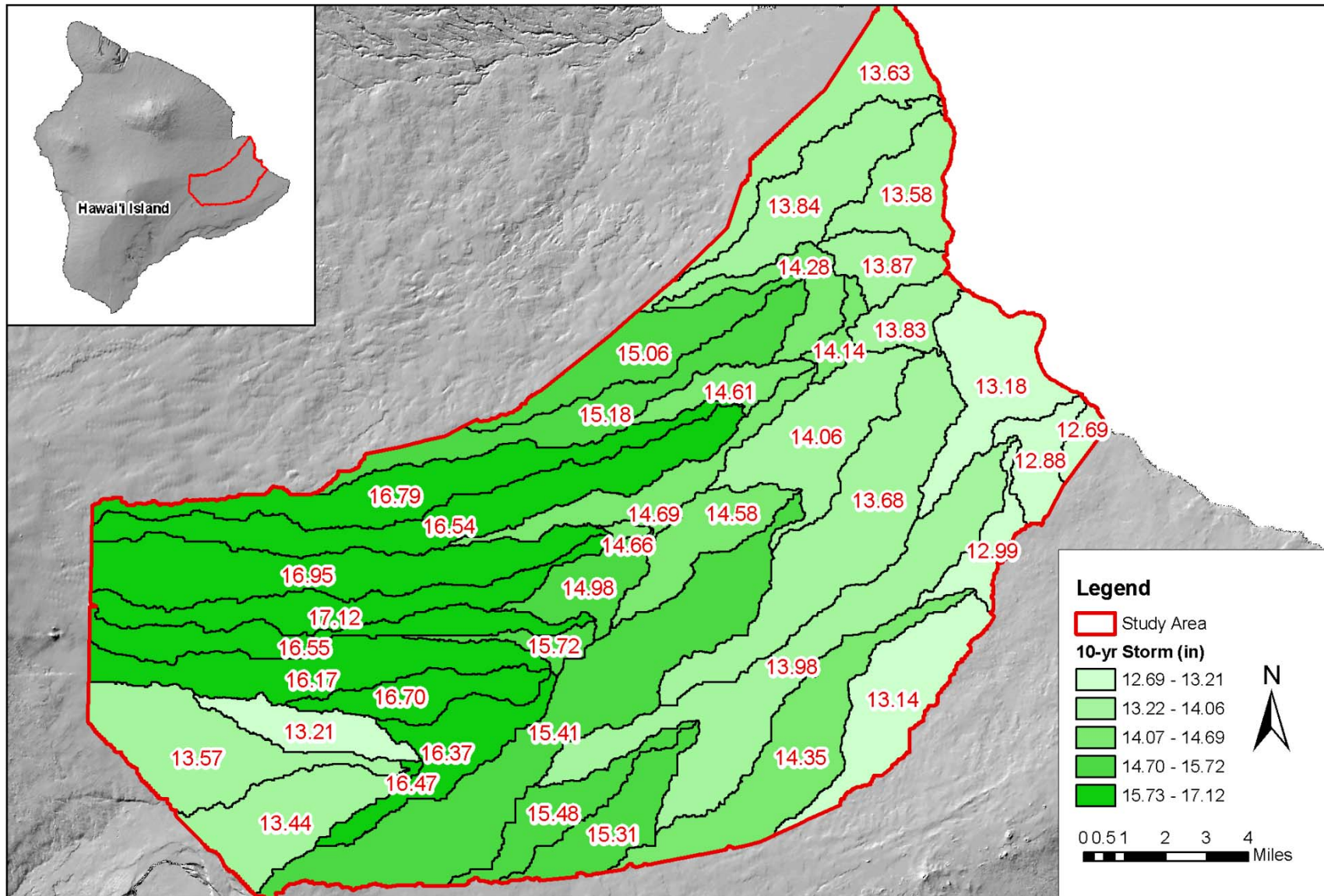


Figure 3 - 6. Rainfall of Each Sub-watershed for 10-yr Storm Return Period.

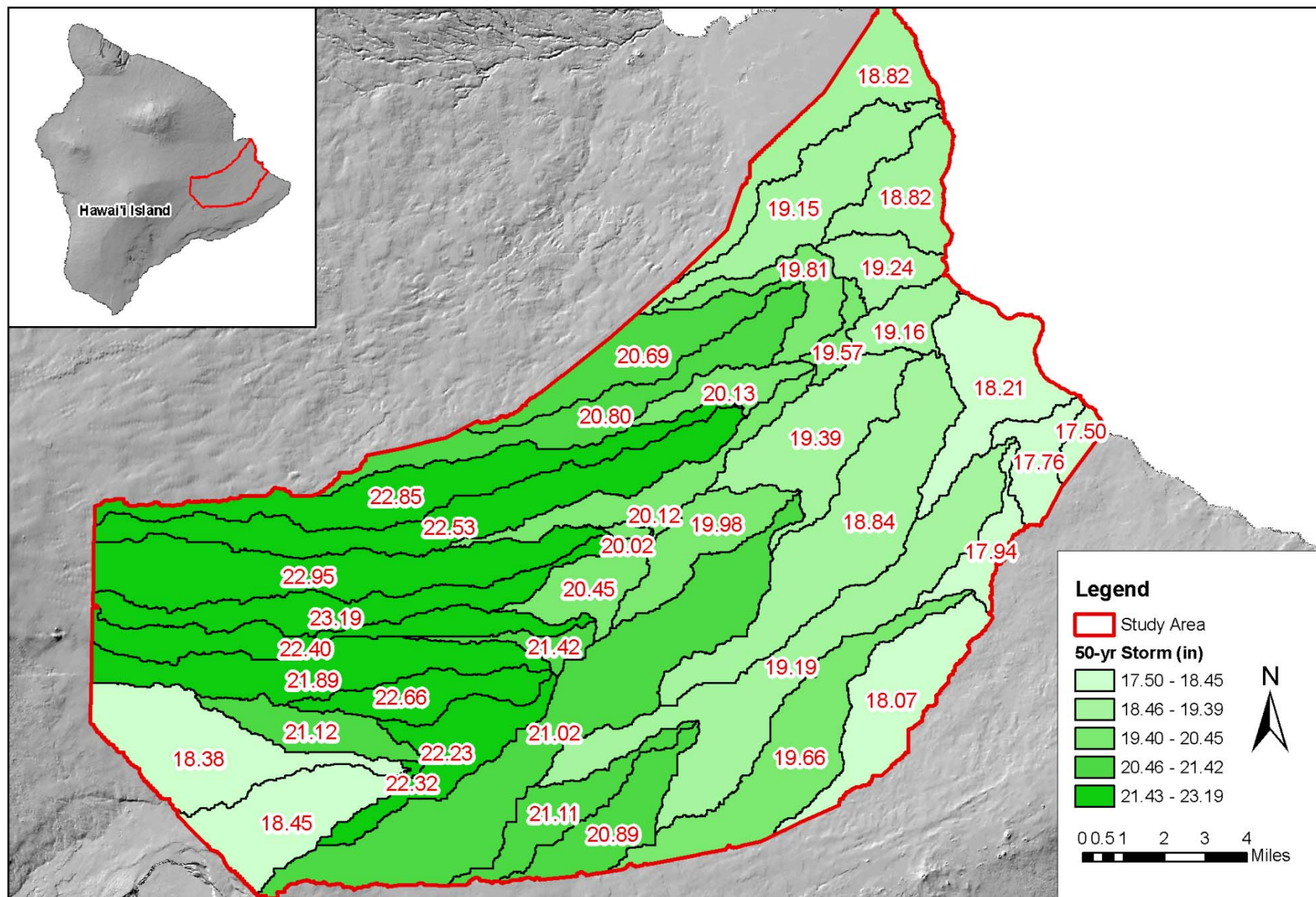


Figure 3 - 7. Rainfall of Each Sub-watershed for 50-yr Storm Return Period.

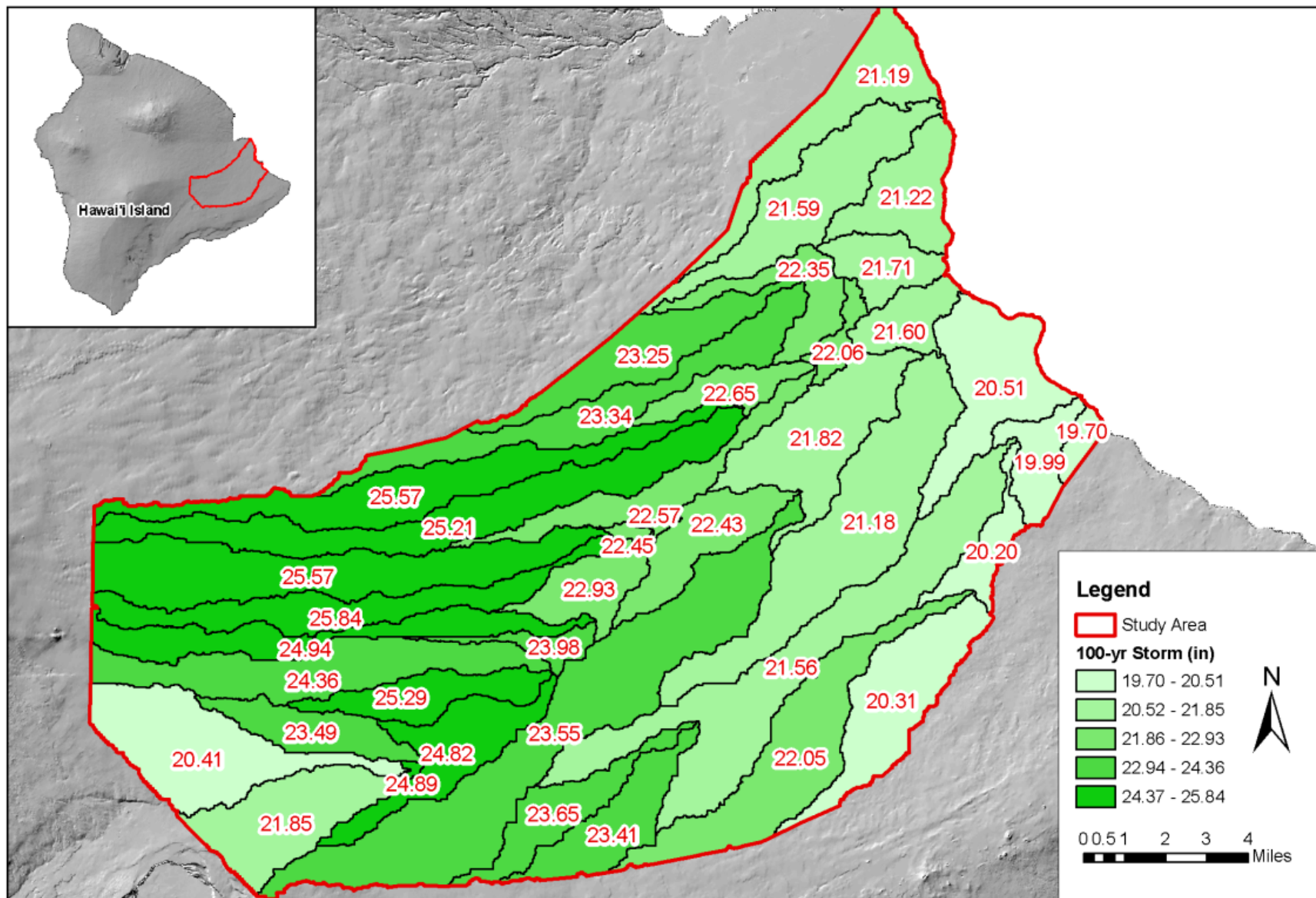


Figure 3 - 8. Rainfall of Each Sub-watershed for 100-yr Storm Return Period.

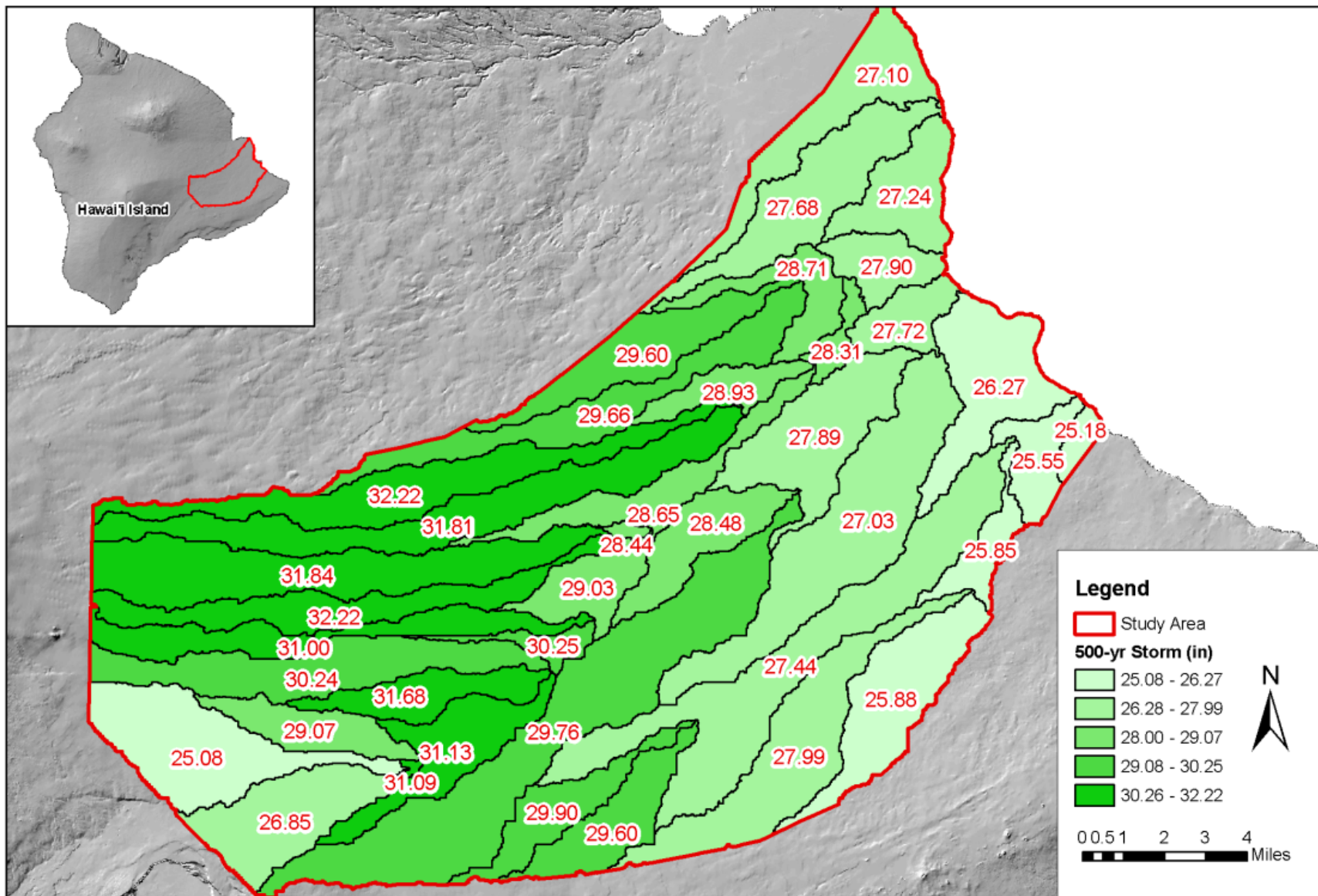


Figure 3 - 9. Rainfall of Each Sub-watershed for 500-yr Storm Return Period.

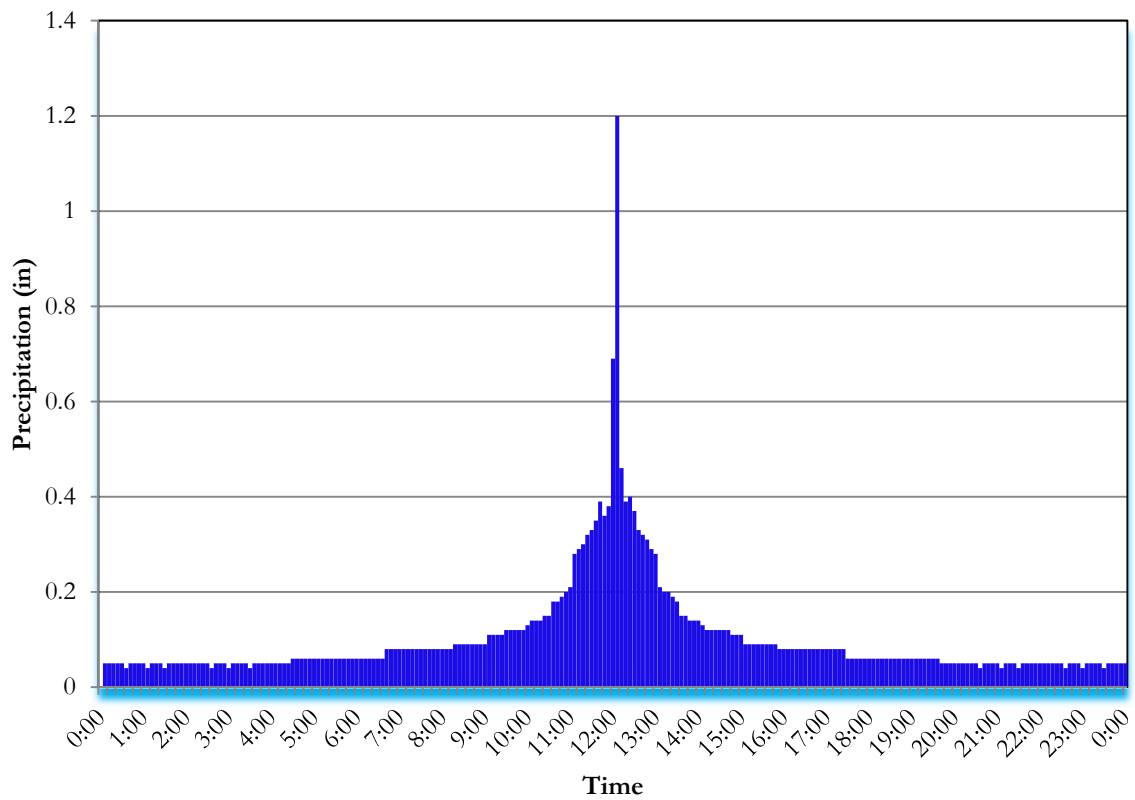


Figure 3 - 10. Designed 100-year 24-hour Rainfall Distribution for Sub-watershed 43 (Typical Hyetograph).



Table 3 - 3. Rainfall for Sub-watersheds Extracted from Atlas 14.

Sub-watershed	ARI (years)	5-min	10-min	15-min	30-min	1-hr	2-hr	3-hr	6-hr	12-hr	24-hr
29	10	0.85	1.16	1.45	2.15	3.1	4.7	5.67	7.72	10.34	13.44
	50	1.08	1.48	1.85	2.75	3.96	6.16	7.47	10.3	14.02	18.45
	100	1.14	1.56	1.95	2.88	4.16	6.26	7.81	11.15	15.79	21.85
	500	1.39	1.9	2.38	3.52	5.08	7.59	9.48	13.68	19.36	26.85
30	10	1.07	1.47	1.84	2.72	3.93	5.81	7.04	9.43	12.64	16.47
	50	1.36	1.86	2.33	3.46	4.99	7.48	9.12	12.44	16.91	22.32
	100	1.48	2.03	2.54	3.76	5.43	8.2	10.02	13.74	18.79	24.89
	500	1.77	2.43	3.04	4.5	6.49	9.87	12.12	16.85	23.27	31.09
34	10	0.94	1.29	1.61	2.39	3.44	5.09	6.17	8.54	11.7	15.48
	50	1.19	1.63	2.04	3.02	4.36	6.57	8.03	11.32	15.75	21.11
	100	1.29	1.77	2.22	3.29	4.74	7.21	8.84	12.55	17.57	23.65
	500	1.53	2.1	2.63	3.89	5.62	8.69	10.72	15.5	22.02	29.9
35	10	0.92	1.26	1.58	2.34	3.38	5	6.07	8.41	11.54	15.31
	50	1.17	1.6	2	2.97	4.28	6.46	7.9	11.15	15.56	20.89
	100	1.27	1.74	2.18	3.23	4.65	7.09	8.69	12.37	17.36	23.41
	500	1.5	2.06	2.58	3.82	5.51	8.54	10.55	15.28	21.75	29.6
37	10	0.97	1.32	1.66	2.45	3.54	5.25	6.4	8.67	11.8	13.21
	50	1.24	1.69	2.12	3.14	4.53	6.78	8.32	11.46	15.77	21.12
	100	1.35	1.85	2.31	3.42	4.94	7.43	9.14	12.65	17.48	23.49
	500	1.62	2.23	2.79	4.12	5.95	8.94	11.03	15.47	21.5	29.07
38	10	0.69	0.94	1.18	1.75	2.52	3.78	4.7	6.78	9.74	13.57
	50	0.9	1.23	1.54	2.28	3.29	4.95	6.19	9.06	13.1	18.38
	100	0.98	1.35	1.68	2.49	3.6	5.43	6.81	10.02	14.52	20.41
	500	1.19	1.62	2.03	3.01	4.34	6.54	8.23	12.26	17.78	25.08
39	10	1.06	1.45	1.81	2.68	3.87	5.72	6.92	9.33	12.54	16.37
	50	1.34	1.83	2.29	3.4	4.9	7.37	8.98	12.31	16.81	22.23
	100	1.46	1.99	2.49	3.69	5.33	8.07	9.86	13.62	18.7	24.82
	500	1.73	2.38	2.97	4.4	6.35	9.72	11.94	16.73	23.24	31.13
42	10	1.09	1.5	1.88	2.78	4.01	5.92	7.15	9.59	12.84	16.7
	50	1.38	1.89	2.37	3.51	5.06	7.61	9.27	12.64	17.18	22.66
	100	1.5	2.06	2.58	3.81	5.5	8.33	10.17	13.97	19.09	25.29
	500	1.79	2.45	3.07	4.54	6.56	10.01	12.29	17.13	23.68	31.68



Puna Flood Study Hydrologic and Hydraulic Report

Sub-water-shed	ARI (years)	5-min	10-min	15-min	30-min	1-hr	2-hr	3-hr	6-hr	12-hr	24-hr
43	10	1.04	1.43	1.78	2.64	3.81	5.62	6.82	9.17	12.35	16.17
	50	1.32	1.81	2.26	3.35	4.84	7.23	8.84	12.08	16.49	21.89
	100	1.44	1.97	2.46	3.65	5.26	7.91	9.7	13.33	18.28	24.36
	500	1.72	2.35	2.94	4.36	6.29	9.49	11.68	16.27	22.51	30.24
45	10	0.97	1.34	1.67	2.48	3.57	5.29	6.4	8.77	11.92	15.72
	50	1.23	1.69	2.11	3.12	4.51	6.82	8.32	11.6	16.02	21.42
	100	1.34	1.83	2.29	3.39	4.9	7.48	9.14	12.84	17.85	23.98
	500	1.58	2.17	2.71	4.01	5.79	8.99	11.07	15.8	22.28	30.25
47	10	1.08	1.48	1.85	2.74	3.95	5.83	7.05	9.46	12.67	16.55
	50	1.36	1.87	2.34	3.46	5	7.48	9.12	12.44	16.91	22.4
	100	1.48	2.03	2.54	3.76	5.43	8.18	9.99	13.72	18.75	24.94
	500	1.76	2.42	3.02	4.48	6.46	9.79	12.02	16.73	23.09	31
49	10	0.85	1.17	1.46	2.16	3.11	4.74	5.71	7.71	10.2	13.14
	50	1.09	1.49	1.86	2.76	3.98	6.23	7.54	10.3	13.87	18.07
	100	1.18	1.62	2.03	3	4.34	6.86	8.33	11.43	15.52	20.31
	500	1.41	1.93	2.41	3.57	5.15	8.37	10.21	14.17	19.61	25.88
50	10	0.88	1.21	1.51	2.23	3.23	4.84	5.86	8.05	10.91	14.35
	50	1.12	1.53	1.92	2.85	4.11	6.31	7.69	10.72	14.76	19.66
	100	1.22	1.67	2.09	3.1	4.47	6.94	8.48	11.89	16.49	22.05
	500	1.45	1.98	2.48	3.68	5.3	8.42	10.34	14.71	20.74	27.99
52	10	1.13	1.55	1.94	2.87	4.14	6.09	7.37	9.86	13.15	17.12
	50	1.42	1.95	2.44	3.62	5.22	7.81	9.52	12.95	17.55	23.19
	100	1.54	2.12	2.65	3.92	5.66	8.54	10.43	14.29	19.46	25.84
	500	1.83	2.51	3.14	4.65	6.72	10.22	12.54	17.43	24.02	32.22
54	10	0.91	1.25	1.56	2.31	3.33	4.96	6	8.29	11.34	14.98
	50	1.15	1.57	1.97	2.91	4.2	6.4	7.8	10.97	15.27	20.45
	100	1.24	1.7	2.13	3.16	4.56	7.01	8.58	12.15	17.02	22.93
	500	1.47	2.01	2.52	3.72	5.37	8.42	10.38	14.96	21.29	29.03
56	10	1.1	1.51	1.89	2.79	4.03	5.92	7.17	9.65	12.93	16.95
	50	1.39	1.9	2.38	3.52	5.07	7.59	9.26	12.68	17.25	22.95
	100	1.5	2.06	2.57	3.81	5.5	8.29	10.14	13.97	19.13	25.57
	500	1.77	2.43	3.04	4.5	6.5	9.89	12.16	17	23.56	31.84



Puna Flood Study Hydrologic and Hydraulic Report

Sub-water-shed	ARI (years)	5-min	10-min	15-min	30-min	1-hr	2-hr	3-hr	6-hr	12-hr	24-hr
58	10	0.89	1.22	1.52	2.25	3.25	4.83	5.85	8.1	11.1	14.66
	50	1.12	1.53	1.92	2.84	4.1	6.24	7.61	10.71	14.94	20.02
	100	1.21	1.66	2.08	3.08	4.44	6.83	8.36	11.86	16.66	22.45
	500	1.43	1.95	2.44	3.62	5.22	8.19	10.11	14.61	20.85	28.44
60	10	0.94	1.29	1.61	2.38	3.44	5.08	6.17	8.52	11.65	15.41
	50	1.19	1.63	2.04	3.02	4.36	6.57	8.03	11.28	15.69	21.02
	100	1.29	1.77	2.22	3.28	4.74	7.2	8.82	12.51	17.5	23.55
	500	1.53	2.1	2.62	3.89	5.61	8.67	10.71	15.44	21.92	29.76
64	10	0.89	1.21	1.52	2.25	3.25	4.85	5.87	8.12	11.07	14.58
	50	1.12	1.54	1.92	2.85	4.11	6.3	7.67	10.78	14.96	19.98
	100	1.22	1.67	2.09	3.09	4.46	6.91	8.44	11.95	16.7	22.43
	500	1.44	1.97	2.46	3.65	5.27	8.34	10.25	14.74	20.96	28.48
65	10	0.83	1.14	1.43	2.11	3.05	4.63	5.57	7.55	10.03	12.99
	50	1.07	1.46	1.83	2.71	3.91	6.1	7.38	10.12	13.69	17.94
	100	1.17	1.6	2	2.96	4.27	6.73	8.17	11.25	15.35	20.2
	500	1.39	1.9	2.38	3.53	5.09	8.23	10.06	14.01	19.48	25.85
66	10	0.87	1.19	1.49	2.21	3.18	4.79	5.79	7.93	10.69	13.98
	50	1.11	1.51	1.9	2.81	4.05	6.26	7.61	10.57	14.49	19.19
	100	1.2	1.65	2.06	3.06	4.41	6.89	8.4	11.73	16.2	21.56
	500	1.43	1.95	2.44	3.62	5.22	8.36	10.25	14.52	20.41	27.44
69	10	1.04	1.43	1.79	2.65	3.83	5.67	6.85	9.35	12.59	16.54
	50	1.31	1.8	2.25	3.34	4.82	7.3	8.89	12.33	16.89	22.53
	100	1.43	1.95	2.44	3.62	5.22	7.99	9.76	13.63	18.79	25.21
	500	1.68	2.31	2.89	4.27	6.17	9.6	11.79	16.71	23.4	31.81
70	10	1.06	1.45	1.82	2.69	3.88	5.74	6.95	9.47	12.76	16.79
	50	1.33	1.83	2.29	3.39	4.89	7.39	9.02	12.48	17.11	22.85
	100	1.45	1.98	2.48	3.67	5.3	8.09	9.9	13.79	19.03	25.57
	500	1.71	2.34	2.93	4.34	6.26	9.72	11.95	16.9	23.68	32.22
71	10	0.8	1.1	1.38	2.04	2.94	4.44	5.34	7.28	9.77	12.69
	50	1.03	1.41	1.76	2.6	3.76	5.83	7.05	9.75	13.31	17.5
	100	1.12	1.53	1.92	2.84	4.09	6.43	7.8	10.84	14.92	19.7
	500	1.33	1.82	2.28	3.37	4.86	7.83	9.55	13.46	18.88	25.18



Puna Flood Study Hydrologic and Hydraulic Report

Sub-water-shed	ARI (years)	5-min	10-min	15-min	30-min	1-hr	2-hr	3-hr	6-hr	12-hr	24-hr
74	10	0.81	1.12	1.4	2.07	2.98	4.51	5.42	7.4	9.92	12.88
	50	1.04	1.43	1.79	2.65	3.82	5.92	7.17	9.91	13.52	17.76
	100	1.14	1.56	1.95	2.88	4.16	6.53	7.92	11.01	15.14	19.99
	500	1.35	1.85	2.31	3.42	4.94	7.96	9.71	13.67	19.17	25.55
80	10	0.89	1.22	1.52	2.26	3.26	4.86	5.87	8.14	11.14	14.69
	50	1.12	1.54	1.93	2.85	4.12	6.29	7.66	10.79	15.03	20.12
	100	1.22	1.67	2.09	3.1	4.47	6.89	8.43	11.96	16.77	22.57
	500	1.44	1.97	2.46	3.65	5.26	8.3	10.21	14.74	21.02	28.65
81	10	0.89	1.22	1.52	2.25	3.25	4.84	5.85	8.14	11.11	14.61
	50	1.13	1.55	1.94	2.87	4.13	6.32	7.69	10.86	15.09	20.13
	100	1.23	1.68	2.11	3.12	4.5	6.95	8.48	12.06	16.88	22.65
	500	1.45	1.99	2.49	3.69	5.32	8.43	10.33	14.93	21.27	28.93
82	10	0.86	1.18	1.47	2.18	3.15	4.75	5.73	7.83	10.52	13.68
	50	1.1	1.5	1.88	2.79	4.02	6.23	7.55	10.46	14.3	18.84
	100	1.2	1.64	2.05	3.03	4.38	6.86	8.34	11.62	16	21.18
	500	1.42	1.94	2.43	3.6	5.19	8.34	10.19	14.4	20.21	27.03
84	10	0.87	1.19	1.48	2.2	3.17	4.74	5.72	7.9	10.75	14.06
	50	1.1	1.51	1.89	2.8	4.04	6.21	7.53	10.56	14.62	19.39
	100	1.2	1.65	2.06	3.05	4.4	6.83	8.31	11.73	16.36	21.82
	500	1.42	1.95	2.44	3.62	5.22	8.3	10.15	14.54	20.66	27.89
89	10	0.82	1.13	1.41	2.09	3.02	4.54	5.46	7.48	10.12	13.18
	50	1.05	1.44	1.8	2.67	3.86	5.96	7.21	10.03	13.8	18.21
	100	1.15	1.57	1.97	2.91	4.2	6.57	7.97	11.15	15.46	20.51
	500	1.36	1.87	2.33	3.46	4.99	8	9.75	13.85	19.57	26.27
93	10	0.92	1.25	1.57	2.32	3.35	5	6.05	8.42	11.5	15.18
	50	1.16	1.59	1.99	2.94	4.24	6.48	7.9	11.17	15.52	20.8
	100	1.26	1.72	2.15	3.19	4.6	7.11	8.7	12.38	17.32	23.34
	500	1.48	2.03	2.54	3.76	5.42	8.58	10.54	15.24	21.7	29.66
96	10	0.86	1.19	1.48	2.2	3.17	4.72	5.69	7.89	10.79	14.14
	50	1.11	1.51	1.9	2.81	4.05	6.19	7.51	10.57	14.71	19.57
	100	1.21	1.65	2.07	3.06	4.42	6.82	8.3	11.76	16.49	22.06
	500	1.43	1.96	2.45	3.63	5.24	8.3	10.15	14.62	20.89	28.31



Sub-water-shed	ARI (years)	5-min	10-min	15-min	30-min	1-hr	2-hr	3-hr	6-hr	12-hr	24-hr
99	10	0.91	1.24	1.56	2.31	3.33	4.96	6.01	8.38	11.44	15.06
	50	1.15	1.58	1.98	2.92	4.22	6.46	7.87	11.13	15.46	20.69
	100	1.25	1.71	2.15	3.18	4.58	7.1	8.67	12.34	17.27	23.25
	500	1.48	2.02	2.53	3.75	5.41	8.58	10.53	15.22	21.68	29.6
102	10	0.85	1.17	1.46	2.16	3.12	4.67	5.62	7.73	10.58	13.83
	50	1.09	1.49	1.87	2.76	3.99	6.13	7.42	10.37	14.43	19.16
	100	1.19	1.62	2.03	3.01	4.35	6.75	8.2	11.54	16.18	21.6
	500	1.41	1.93	2.41	3.57	5.16	8.21	10.02	14.34	20.5	27.72
108	10	0.87	1.19	1.49	2.21	3.19	4.74	5.72	7.95	10.88	14.28
	50	1.11	1.52	1.91	2.83	4.08	6.22	7.56	10.67	14.86	19.81
	100	1.22	1.66	2.08	3.08	4.45	6.85	8.36	11.87	16.67	22.35
	500	1.44	1.98	2.47	3.66	5.28	8.34	10.23	14.78	21.13	28.71
110	10	0.85	1.16	1.46	2.16	3.11	4.65	5.6	7.73	10.58	13.87
	50	1.09	1.49	1.86	2.76	3.98	6.09	7.38	10.37	14.46	19.24
	100	1.19	1.62	2.03	3.01	4.34	6.71	8.16	11.55	16.22	21.71
	500	1.41	1.93	2.41	3.57	5.16	8.17	9.99	14.39	20.58	27.9
112	10	0.83	1.14	1.43	2.11	3.05	4.55	5.48	7.57	10.39	13.58
	50	1.06	1.46	1.83	2.7	3.9	5.97	7.24	10.15	14.19	18.82
	100	1.16	1.59	1.99	2.95	4.25	6.58	8	11.29	15.91	21.22
	500	1.38	1.89	2.36	3.49	5.04	8.01	9.78	14.03	20.15	27.24
115	10	0.84	1.15	1.44	2.13	3.08	4.59	5.53	7.68	10.58	13.84
	50	1.07	1.47	1.84	2.73	3.94	6.02	7.3	10.29	14.43	19.15
	100	1.17	1.6	2.01	2.97	4.29	6.64	8.06	11.44	16.16	21.59
	500	1.39	1.9	2.38	3.52	5.08	8.07	9.85	14.2	20.45	27.68
117	10	0.82	1.13	1.41	2.09	3.02	4.5	5.42	7.54	10.46	13.63
	50	1.05	1.44	1.8	2.67	3.85	5.91	7.15	10.1	14.23	18.82
	100	1.15	1.57	1.96	2.91	4.19	6.51	7.89	11.21	15.93	21.19
	500	1.35	1.85	2.32	3.44	4.96	7.92	9.61	13.87	20.11	27.1

3.4 Basin Loss

Basin loss was estimated using the Green-Ampt infiltration method. The parameters of the Green-Ampt method were determined from several references. These were: (1) *Application of the Green-Ampt Infiltration Equation to Watershed Modeling*. Water Resources Bulletin, Vol. 28 (James et al. 1992); (2) Fullerton's Master Thesis, Colorado State University (1983);



(3) USACE *Technical Engineering and Design Guide*, No. 19 (1997). Several justifications are described as follows:

i. Saturated Soil Conductivity (K_{sat})

The most important parameter is the saturated hydraulic conductivity. The soil conductivity depends on soil types. Soil types in the Puna study area are listed in Table 3-4 and shown in Figure 3-11. Lau and Mink (2006) pointed out that the values of saturated hydraulic conductivity in Hawai'i's soils are typically a few inches per day. Rocky mucks are thin soil layers on unweathered pāhoehoe or 'a'ā. The K_{sat} of the rock is very low except where there are fractures. These fractures would be plugged with the muck resulting in lower soil permeability which inhibits flow and the effect the fractures. It is assumed that 'a'ā would have high K_{sat} value, and the initial K_{sat} value was set at the maximum of 10 in/hr. Unweathered pāhoehoe with no soil would have lower permeability, but will increase with fractures. The stony clay loams were slightly more permeable than the clay loams. Figure 3-12 shows the saturated soil conductivities of Puna study area

ii. Porosity

Soil porosities range from a 0.08 for agriculture land to more than 0.7 for forest area soils. Rocky mucks are thin soil layers on unweathered pāhoehoe or 'a'ā. It is reasonable to assume that the porosity is a combination of both soil and rock porosities. The porosity of the rock is about 0.1 and the porosity of the soil is much higher. The usable porosity of the rock is about 0.1, but fractures near the surface may increase this porosity to about 0.2.

iii. Impervious

The Puna study area is mostly undeveloped. The roofs of structures, roadways and other hard surface areas are negligible. The impervious values are set as zero.

iv. Soil Suction

Soil suction assumed to be the canopy interception storage. Soil suction is a function of vegetation type. The rain can be stored from a particular event. The value selected was based on Fullerton's estimate for Forest Floor.

v. Soil Moisture Deficit

The soil moisture deficit is a rough estimate base on the FLO-2D manual (2006) Table 5. The soil moisture deficit used in HEC-HMS model was 0.3 for most soil types, which was implemented by an initial content 0.16 and a saturated content 0.46. This assumes that the soil retains a certain level of moisture. 'A'ā and pāhoehoe soils retain less because they are fractured and subject to solar drying.

Table 3-5 gives Green-Ampt infiltration parameters determination for Puna Study Area. The Green-Ampt parameters for each sub-watershed were calculated by averaging the values



from a GIS shape file containing the data of the infiltration parameters. Table 3-6 shows the average saturated hydraulic conductivities for each sub-watershed.

Table 3 - 4. Soil Types in Puna Study Area.

NRCS Description	Soil Type	Percent Slopes	Area (acres)
Akc	‘Akaka silty clay loam	0 to 10	19,969
HIC	Hilea silty clay loam	6 to 12	4,354
HoC	Hilo silty clay loam	0 to 10	753
HoD	Hilo silty clay loam	10 to 20	34
rKAD	Kahalu‘u extremely rocky muck	6 to 20	1,638
rKFD	Keaukaha extremely rocky muck	6 to 20	7,634
rKGD	Ke‘ei extremely rocky muck	6 to 20	32,639
rKHD	Kekake extremely rocky muck	6 to 20	88
rKXD	Kīloa extremely stony muck	6 to 20	10,028
rLLD	Lalaau extremely stony muck	6 to 20	3,219
rLV	Lava flows, ‘a‘ā	-	91
rLW	Lava flows, pāhoehoe	-	50,363
rMUB	Manu silt loam	2 to 6	1,149
OSD	‘Ōhi‘a extremely stony silty clay loam	0 to 20	4,068
OHC	‘Ōhi‘a silty clay loam	0 to 10	6,580
OID	‘Ōla‘a extremely stony silty clay loam	0 to 20	1,549
OaC	‘Ōla‘a silty clay loam	0 to 10	1,990
rOPE	‘Ōpihikao extremely rocky muck	3 to 25	158
PeC	Pana‘ewa very rocky silty clay loam	0 to 10	2,968
rPAE	Pāpa‘i extremely stony muck	3 to 25	12,182
POD	Pi‘ihonua extremely stony silty clay loam	6 to 20	113
PND	Pi‘ihonua silty clay loam	6 to 20	7,275
POD	Puauulu silt loam	0 to 10	6,692
PND	Puhimau silt loam	2 to 6	1,022
PPC	Pu‘uk‘ala very rocky silt loam	6 to 12	47
RB	Rough broken land	-	29

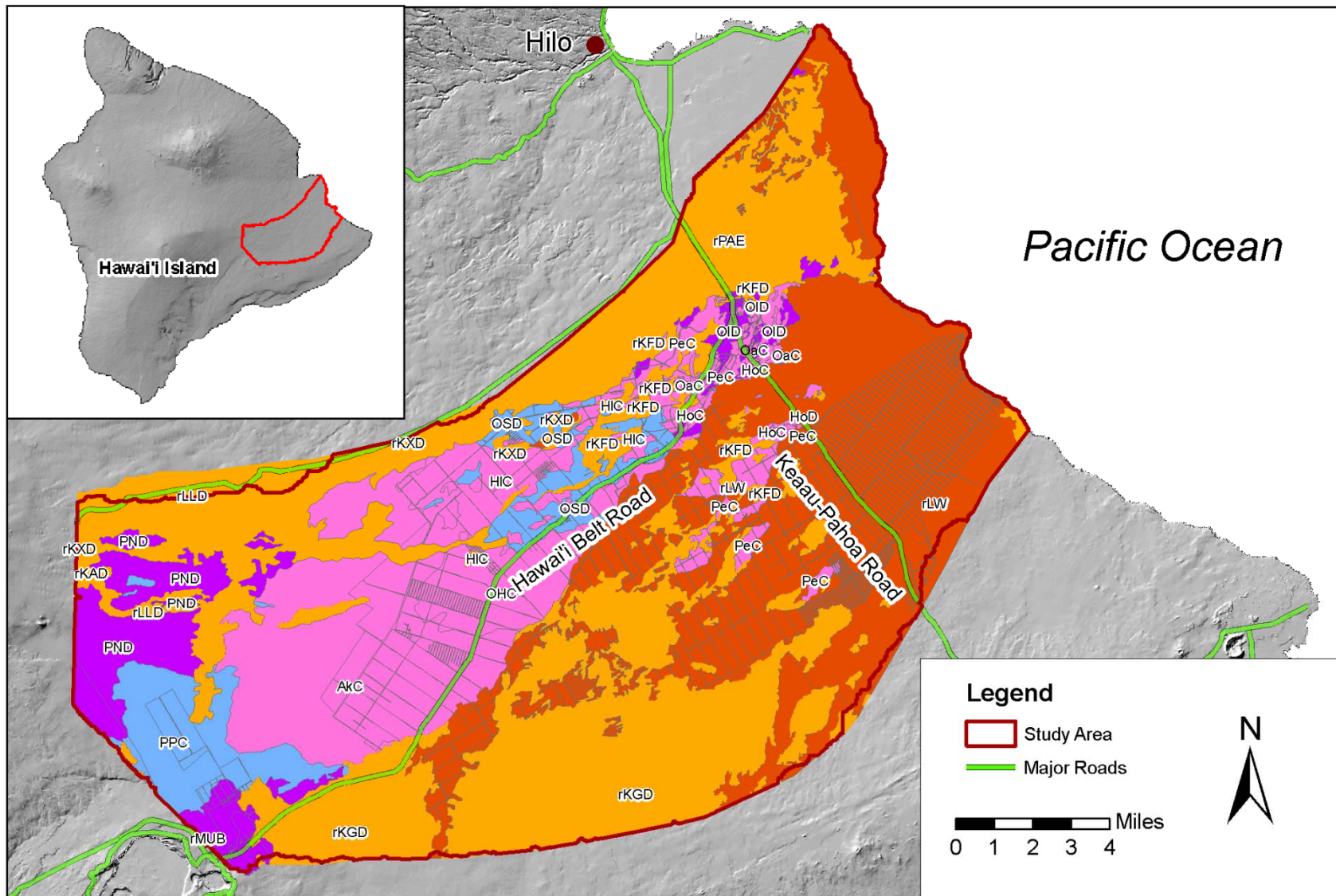


Figure 3 - 11. Soil Type for Puna Study Area.

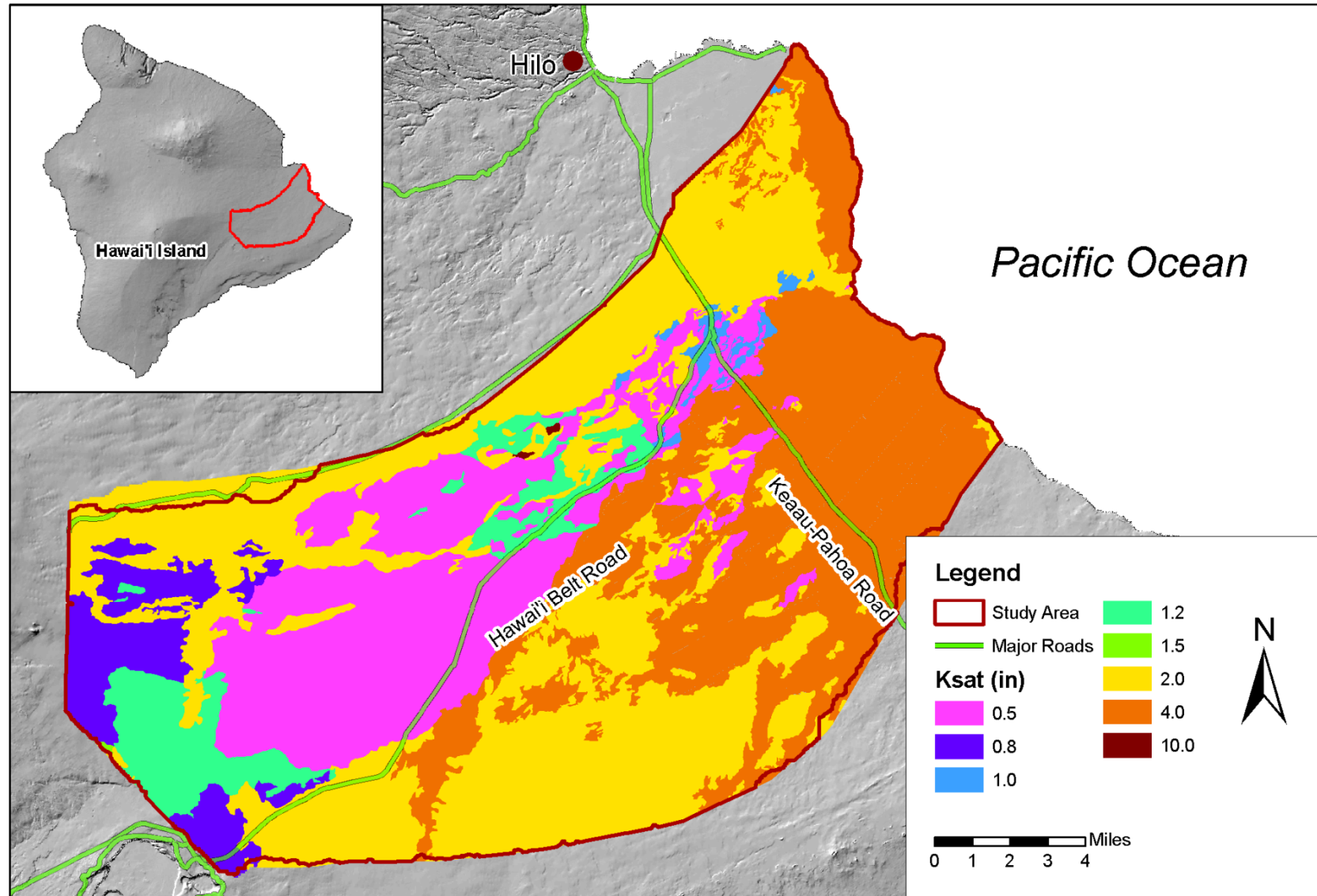


Figure 3 - 12. Saturated Soil Conductivities for Puna Watershed.



Table 3 - 5. Green-Ampt Infiltration Parameters Determination for Puna Study Area.

Soil Description	First_M USY	K _{sat} (in/hr)	Ref. Used	Porosi ty	Porosi ty Ref*	Impervi ous area	Ref. Used	Soil Suction (in)	Ref. Used	Abstractio n (intercept ion) (inches)	Ref. Used	Soil Moistur e Deficit %	Ref. Used
‘Akaka silty clay loam	AkC	0.5	3	0.471	4	0	1	10.8	2	0.5	1	0.3	1
Hilea silty clay loam	HIC	0.5	3	0.471	4	0	1	10.8	2	0.5	1	0.3	1
Hilo silty clay loam	HoC	0.5	3	0.471	4	0	1	10.8	2	0.5	1	0.3	1
Hilo silty clay loam	HoD	0.5	3	0.471	4	0	1	10.8	2	0.5	1	0.3	1
Kahalu‘u extremely rocky muck	rKAD	2	1	0.2	1	0	1	2	1	0.5	1	0.3	1
Keaukaha extremely rocky muck	rKFD	2	1	0.2	1	0	1	2	1	0.5	1	0.3	1
Ke‘ei extremely rocky muck	rKGD	2	1	0.2	1	0	1	2	1	0.5	1	0.3	1
Kekake extremely rocky muck	rKHD	2	1	0.2	1	0	1	2	1	0.5	1	0.3	1
Kīloa extremely stony muck	rKXD	2	1	0.2	1	0	1	2	1	0.5	1	0.3	1
Lalaa extremely stony muck	rLJD	2	1	0.2	1	0	1	2	1	0.5	1	0.3	1
Lava flows, ‘a‘ā	rLV	10	1	0.15	1	0	1	2	1	0.5	1	0.1	1
Lava flows,pāhoehoe	rLW	4	1	0.15	1	0	1	2	1	0.5	1	0.1	1
Manu silt loam	MND	1.2	1	0.2	1	0	1	2	1	0.5	1	0.3	1
‘Ōhi‘a extremely stony silty clay loam	rMUB	0.8	3	0.501	4	0	1	6.6	2	0.5	1	0.3	1
‘Ōhi‘a silty clay loam	OSD	1.2	1	0.471	4	0	1	10.8	2	0.5	1	0.3	1
‘Ōla‘a extremely stony silty clay loam	OHC	0.5	3	0.471	4	0	1	10.8	2	0.5	1	0.3	1
‘Ōla‘a silty clay loam	OID	1	1	0.471	4	0	1	10.8	2	0.5	1	0.3	1
‘Ōpihikao extremely rocky muck	OaC	0.5	3	0.471	4	0	1	10.8	2	0.5	1	0.3	1
Pana‘ewa very rocky silty clay loam	rOPE	2	1	0.2	1	0	1	2	1	0.5	1	0.3	1



Puna Flood Study
Hydrologic and Hydraulic Report

Pāpa'i extremely stony muck	PeC	0.5	3	0.471	4	0	1	10.8	2	0.5	1	0.3	1
Pi'ihonua extremely stony silty clay loam	rPAE	2	1	0.2	1	0	1	2	1	0.5	1	0.3	1
Pi'ihonua silty clay loam	POD	1.2	1	0.471	4	0	1	10.8	2	0.5	1	0.3	1
Puauulu silt loam	PND	0.5	3	0.471	4	0	1	10.8	2	0.5	1	0.3	1
Puhimau silt loam	PPC	0.8	3	0.501	4	0	1	6.6	2	0.5	1	0.3	1
Pu'uk'ala very rocky silt loam	rPHB	0.8	3	0.501	4	0	1	6.6	2	0.5	1	0.3	1
Rough broken land	PTC	1.5	1	0.501	4	0	1	6.6	2	0.5	1	0.3	1
'Akaka silty clay loam	RB	1.2	1	0.2	1	0	1	2	1	0.5	1	0.3	1
References used to determine Green-Ampt infiltration parameters													
(1) Estimated by Oceanit hydrogeologist.													
(2) <i>Application of the Green-Ampt Infiltration Equation to Watershed Modeling</i> . Water Resources Bulletin, Vol. 28 (James et al. 1992)													
(3) Fullerton, 1983													
(4) USACE Technical Engineering and Design Guide No 19, 1997.													



Table 3 - 6. Average Saturated Hydraulic Conductivities for Sub-watersheds.

Sub-watershed	Saturated Hydraulic Conductivity Classification (in/hr)								Total (Acres)	Average Conductivity (in/hr)
	0.50	0.80	1.00	1.20	1.50	2.00	5.00	10.00		
	Area in Each Saturated Hydraulic Conductivity Classification (acres)									
29	401.4	3653.7				982.1			5037.2	1.01
30	75.3					24.6			99.9	0.87
34						2872.2	109.9		2982.1	2.07
35						3431.1	37.3		3468.4	2.02
37	2180.4	357.9				141.9			2680.2	0.62
38	2178.0	4220.9		0.0	46.7	274.2			6719.9	0.76
39	1885.4					1501.0	659.7		4046.1	1.63
42	2859.8						0.9		2860.7	0.50
43	5562.1	345.0				432.2	0.4		6339.6	0.62
45	704.6					94.1	220.5		1019.3	1.40
47	3885.3					503.2			4388.6	0.67
49						1575.1	3957.4		5532.5	3.43
50						5762.1	1380.3		7142.4	2.39
52	3404.3			76.2		1411.6			4892.1	0.94
54	2105.9					128.5	419.7		2654.1	1.13
56	5002.9			486.7		3133.2			8622.7	1.08
58	112.3			124.8			4.9		242.0	0.93
60	436.9	282.7				9727.3	4139.8		14586.6	2.50
64	223.2					845.2	2419.2		3487.6	3.29
65							1762.2		1762.2	4.00
66	205.4					5371.1	5854.2		11430.7	3.00
69	3329.7		44.8	1151.8		3655.9			8182.2	1.27
70	3040.9			411.7		3164.9		17.2	6634.8	1.28
71						145.6	514.1		659.7	3.56
74						12.5	2132.4		2144.9	3.99
80	1346.1		89.0	1008.9		93.3	977.5		3514.9	1.73
81	1052.9		91.5	42.1		582.8	75.4		1844.8	1.16
82	260.4					1771.7	8234.9		10267.0	3.57
84	1135.9					889.3	3859.6		5884.8	3.02
89							5534.7		5534.7	4.00
93	1235.8		484.2	866.9		2916.6		73.5	5577.1	1.56
96	303.9		203.0			9.3	415.8		932.1	2.19
99	166.3		95.7	39.6		4140.7			4442.2	1.92
102						0.0	2003.3		2003.3	4.00
108	772.7		334.1			1440.0			2546.8	1.41
110	39.6		169.4			1148.8	835.6		2193.4	2.66
112						1753.6	1730.1		3483.7	2.99
115						4867.3	985.7		5853.0	2.34
117			36.9			2759.3	2058.9		4855.0	2.84
Total	43907.6	8860.2	1548.6	4208.7	46.7	67562.6	50324.1	90.7	176549.3	2.11



3.5 Estimation of Time of Concentrations

Time of concentration determination is necessary for preparing the transform method for a selected unit hydrograph in the HEC-HMS model. The standard TR-55 methodology (NRCS 1986) was employed to calculate the time of concentration (T_c) for each sub-watershed. Time of concentration (T_c) was computed by summing the T_c values of three consecutive flow segments: sheet flow, shallow concentrated flow, and channel flow. Based on the TR-55 method, traveling times for these three flows were added together to calculate time of concentration. The sheet flow segment describes the time period from raindrop impact until overland flow accumulates to a depth of about 0.1 foot. The sheet flow segment and it is calculated using Manning's kinematic solution, dependent on Manning's roughness coefficient "n", the flow length, the rainfall amount, and the land slope. For this study, the sheet flow characteristics of all sub-watersheds assumed a Manning's roughness coefficient n of 0.040 (representing light underbrush surface conditions) and a flow length of 100 feet. The land slope value for each sub-watershed was obtained from the LiDAR topographic data and is shown in Table 3-7.

Manning's "n" values for the sheet flow terrain were selected from Table 3-1 of TR 55 (NRCS 1986). For the open channel flow segments, manning's "n" values were selected from *Roughness Characteristics of Natural Channels* (Barnes 1967) and the guideline specified by *Open Channel Hydraulics* (Chow 1959).

Based on the TR-55 method, the following equations were used to calculate the travel times (T_t) of each flow segment:

i. Sheet Flow:

$$T_t = \frac{0.007(nL)^{0.8}}{(P_2)^{0.5} S^{0.4}}$$

L = Flow length (feet), 300 feet maximum

P_2 = 2-yr, 24-hr rainfall amount at the sub-basin (in), NOAA Precipitation Frequency Data

S = Average land slope (feet vertical/feet horizontal)

n = Manning's roughness coefficient for sheet flow

ii. Shallow Concentrated Flow:

$$T_t = \frac{L}{3600 V}$$

If paved surface:

$$V = 20.3282 S^{0.5}$$



If unpaved surface:

$$V = 16.1345 S^{0.5}$$

L = Length of shallow concentrated flow path (feet)

S = Average watercourse slope (feet vertical/feet horizontal)

iii. Channel Flow:

$$T_t = \frac{L}{3600 V}$$

Where,

$$V = \frac{1.49}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}$$

L = Length of channel (feet)

S = Average channel slope (feet vertical/feet horizontal)

R = Hydraulic radius of bank full open channel or culvert flowing full (feet). The hydraulic radius equals the cross sectional flow area (feet²) divided by the wetted perimeter (feet).

n = Manning's roughness coefficient for open channel flow

iv. Time of Concentration:

$$T_c = T_{t(\text{sheet})} + T_{t(\text{shallow concentrated})} + T_{t(\text{channel})}$$

The T_c Values for the sub-watershed are listed in Table 3-7 and ranged from about 0.3 hour to 4.7 hours. These T_c values were adjusted as part of the HEC-HMS model calibration.

3.6 Hydrograph Transform Parameters

The Snyder peaking coefficient of 0.45 was the initial value for each sub-watershed. The initial lag time parameters were obtained from the T_c calculation, where lag equals to 0.6 times T_c . These initial values were adjusted in the calibration process to provide more reasonable representations for each sub-watershed.



Table 3 - 7. Time of Concentration Values for Puna Study Area.

Sub-watershed	Drainage area (mi ²)	Sheet Flow Characteristics					Shallow Concentrated Flow				Channel Flow Characteristics							Total T _c (hr)
		Manning's n	Flow Length (ft)	Two-Year 24-hour Rainfall (in)	Land Slope	T _i (hr)	Surface Description	Flow Length (ft)	Slope	T _i (hr)	Flow Length (ft)	Cross Section area (ft ²)	Wetted Perimeter (ft)	Channel Slope	Manning's n	Velocity (ft/s)	T _i (hr)	
29	7.982	0.4	100	9.35	0.0457	0.150	Unpaved	25000	0.0464	1.998	7500	60	35	0.040	0.065	6.567	0.317	2.466
30	0.156	0.4	100	10.79	0.0410	0.146	Unpaved	1200	0.0406	0.103	1050	200	150	0.041	0.065	5.623	0.052	0.301
34	4.676	0.4	100	10.23	0.0385	0.154	Unpaved	16000	0.0365	1.442	18000	60	35	0.039	0.065	6.475	0.772	2.368
35	5.462	0.4	100	10.11	0.0383	0.155	Unpaved	15000	0.0382	1.321	17500	60	35	0.038	0.065	6.384	0.761	2.238
37	4.188	0.4	100	10.12	0.0500	0.139	Unpaved	21000	0.0460	1.686	7000	60	35	0.040	0.065	6.567	0.296	2.121
38	10.575	0.4	100	8.65	0.0500	0.151	Unpaved	28000	0.0464	2.237	12000	120	80	0.053	0.065	6.937	0.481	2.869
39	6.322	0.4	100	10.76	0.0500	0.135	Unpaved	16000	0.0713	1.032	20000	120	80	0.042	0.065	6.156	0.902	2.070
42	4.47	0.4	100	10.97	0.0720	0.116	Unpaved	24500	0.0555	1.790	9600	60	35	0.040	0.065	6.533	0.408	2.314
43	9.968	0.4	100	10.54	0.0850	0.111	Unpaved	41000	0.0566	2.967	14000	60	35	0.044	0.065	6.910	0.563	3.641
45	1.643	0.4	100	10.37	0.0620	0.126	Unpaved	9000	0.0889	0.520	8000	120	100	0.030	0.065	4.484	0.496	1.142
47	6.909	0.4	100	10.80	0.0960	0.104	Unpaved	48000	0.0579	3.434	15000	60	35	0.047	0.065	7.093	0.587	4.125
49	8.748	0.4	100	8.60	0.0410	0.164	Unpaved	20500	0.0400	1.765	18000	60	35	0.029	0.065	5.581	0.896	2.824
50	11.267	0.4	100	9.44	0.0335	0.170	Unpaved	27000	0.0315	2.619	34000	60	35	0.031	0.065	5.781	1.634	4.422
52	7.673	0.4	100	11.22	0.1220	0.093	Unpaved	45000	0.0591	3.187	22000	60	35	0.048	0.065	7.207	0.848	4.127
54	4.147	0.4	100	9.88	0.0480	0.144	Unpaved	11500	0.0460	0.923	12700	60	35	0.041	0.065	6.648	0.531	1.597
56	13.594	0.4	100	11.09	0.0950	0.103	Unpaved	44000	0.0564	3.191	17200	60	40	0.069	0.065	7.868	0.607	3.901
58	0.378	0.4	100	9.67	0.0376	0.160	Unpaved	1800	0.0376	0.160	5000	100	80	0.038	0.065	5.156	0.269	0.589
60	22.874	0.4	100	10.17	0.0479	0.142	Unpaved	23000	0.0475	1.817	49000	400	300	0.034	0.065	5.088	2.675	4.634
64	5.449	0.4	100	9.60	0.0345	0.166	Unpaved	15000	0.0350	1.380	14000	60	35	0.032	0.065	5.874	0.662	2.209
65	2.753	0.4	100	8.47	0.0328	0.180	Unpaved	6500	0.0320	0.626	20500	400	300	0.028	0.065	4.647	1.225	2.032
66	17.86	0.4	100	9.18	0.0438	0.154	Unpaved	10500	0.0427	0.875	62000	400	300	0.028	0.065	4.647	3.706	4.736
69	12.826	0.4	100	10.92	0.1080	0.099	Unpaved	42000	0.0619	2.906	41000	60	35	0.046	0.065	7.068	1.611	4.616
70	10.425	0.4	100	11.07	0.1100	0.097	Unpaved	37000	0.0611	2.577	45500	60	35	0.048	0.065	7.220	1.751	4.425
71	1.147	0.4	100	8.28	0.0265	0.199	Unpaved	4000	0.0255	0.431	6000	60	35	0.025	0.065	5.192	0.321	0.951
74	3.414	0.4	100	8.41	0.0278	0.194	Unpaved	7500	0.0266	0.792	12000	400	300	0.026	0.065	4.478	0.744	1.730
80	5.492	0.4	100	9.68	0.0396	0.157	Unpaved	25000	0.0504	1.917	29000	400	300	0.035	0.065	5.195	1.551	3.624



Puna Flood Study Hydrologic and Hydraulic Report

Sub-watershed	Drainage area (mi²)	Sheet Flow Characteristics					Shallow Concentrated Flow				Channel Flow Characteristics							Total T _c (hr)
		Manning's n	Flow Length (ft)	Two-Year 24-hour Rainfall (in)	Land Slope	T _i (hr)	Surface Description	Flow Length (ft)	Slope	T _i (hr)	Flow Length (ft)	Cross Section area (ft²)	Wetted Perimeter (ft)	Channel Slope	Manning n	Velocity (ft/s)	T _i (hr)	
81	2.883	0.4	100	9.56	0.0402	0.157	Unpaved	13600	0.0426	1.134	10500	400	300	0.030	0.065	4.848	0.602	1.892
82	16.042	0.4	100	8.95	0.0386	0.165	Unpaved	12000	0.0377	1.064	48000	200	150	0.027	0.065	4.563	2.922	4.151
84	9.195	0.4	100	9.18	0.0431	0.155	Unpaved	6500	0.0420	0.546	30000	400	300	0.022	0.065	4.119	2.023	2.725
89	8.65	0.4	100	8.59	0.0304	0.185	Unpaved	6200	0.0293	0.624	19000	100	80	0.019	0.065	3.667	1.439	2.248
93	8.862	0.4	100	10.00	0.0576	0.133	Unpaved	26600	0.0560	1.935	44200	60	35	0.038	0.065	6.401	1.918	3.986
96	1.456	0.4	100	9.20	0.0233	0.199	Unpaved	1000	0.0240	0.111	11800	200	150	0.022	0.065	4.119	0.796	1.105
99	7.239	0.4	100	9.90	0.0468	0.145	Unpaved	19000	0.0450	1.542	24000	60	30	0.040	0.065	7.278	0.916	2.603
102	3.132	0.4	100	8.99	0.0300	0.182	Unpaved	2000	0.0289	0.203	13000	1200	1000	0.045	0.065	5.491	0.658	1.042
108	3.979	0.4	100	9.29	0.0275	0.185	Unpaved	14500	0.0275	1.505	6000	150	120	0.015	0.065	3.258	0.512	2.202
110	3.428	0.4	100	9.00	0.0105	0.276	Unpaved	7000	0.0171	0.920	8700	400	300	0.007	0.065	2.306	1.048	2.245
112	5.449	0.4	100	8.82	0.0213	0.210	Unpaved	5600	0.0195	0.690	10000	60	35	0.008	0.065	2.937	0.946	1.846
115	9.23	0.4	100	9.01	0.0389	0.163	Unpaved	11000	0.0380	0.972	26500	100	80	0.014	0.065	3.113	2.364	3.499
117	8.502	0.4	100	8.89	0.0578	0.140	Unpaved	9000	0.0450	0.730	32000	100	80	0.012	0.065	2.914	3.051	3.921



3.7 Model Calibration

The calibration rainfall data were from the NOAA Hydronet rain gages HI81, HI83, HI91, HI92, and HI94 (see Section 2.3.1). The simulation time period was 42 hours from 0:00, 11/1/2000, to 18:00, 11/2/2000. Since there are no stream gage data available within the Puna study area, a second hydrologic model (FLO-2D) was applied for the same study area for comparative purposes. (Appendix A).

The gage weights method was used to determine the rainfall amount for calibration purposes. A Thiessen Polygon mechanism was initially applied to determine the gage weight for each sub-watershed. Figure 3-13 shows the Thiessen Polygon for this study. After the rainfall pattern, data quality, storm movement and distribution were considered; the final gage and time weights and relevant 42-hour rainfall of the November 1 to 2, 2000, storm for the sub-watersheds were determined as shown in Table 3-8.

Both the HEC-HMS and FLO-2D models were run for the calibration storm event (November 1 to 2, 2000). The results of both models are shown in Table 3-9. The results of the two models matched closely to each other, with an average difference of 11%.

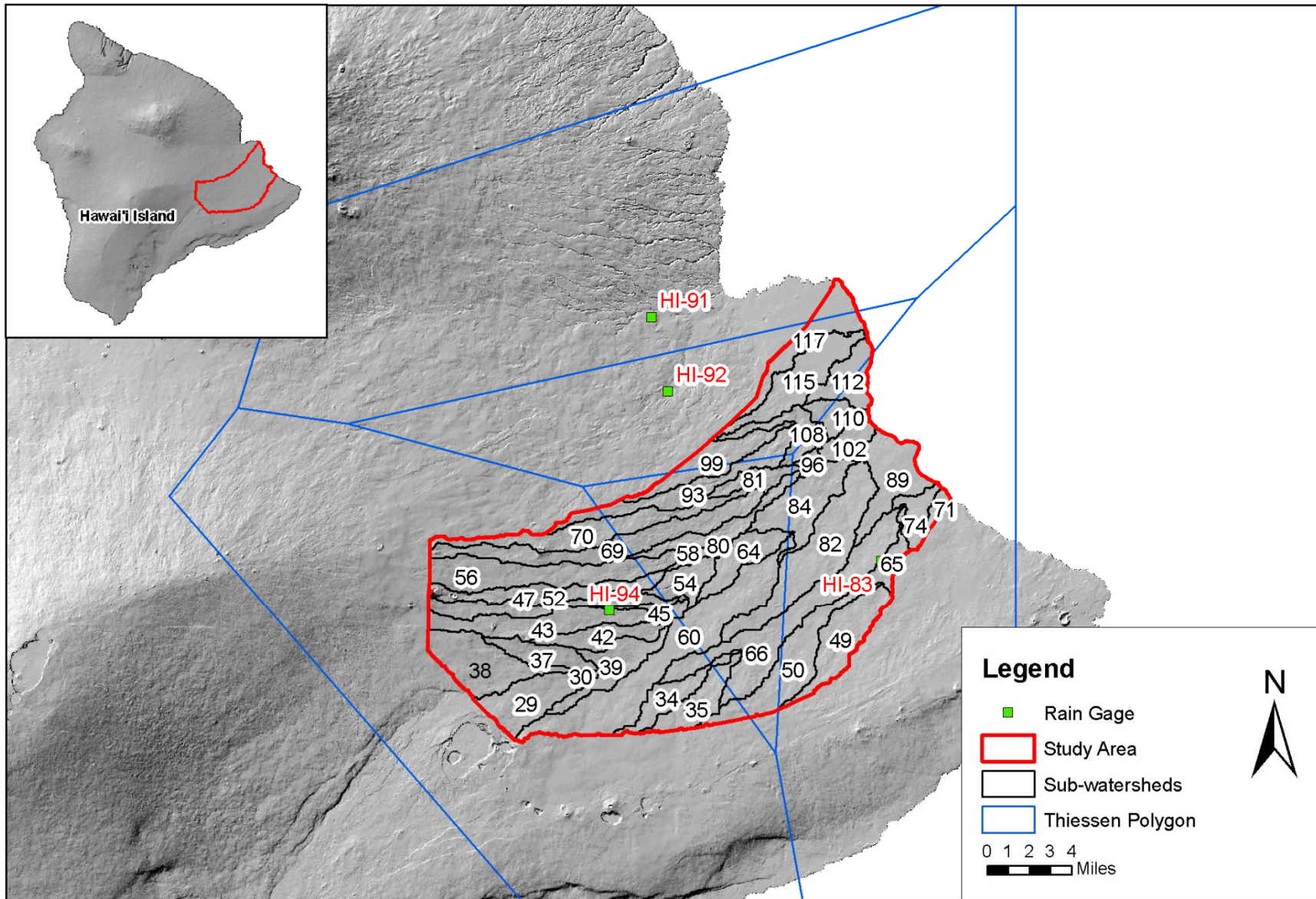


Figure 3 - 13. Rain Gages Thiessen Polygon for November 1st to 2nd, 2000, Storm.



Table 3 - 8. Gage Depth and Time Weights for November 1 to 2, 2000, Storm.

Sub-watershed	Area(mi ²)	Precipitation Gage Depth (Time) Weights					42-hr Rainfall (in)
		HI81	HI83	HI91	HI92	HI94	
29	7.982		0.5(0)			0.5(1)	23.62
30	0.156		0.5(0)			0.5(1)	23.62
34	4.676	0.3(0.5)	0.3(0)			0.4(0.5)	26.81
35	5.462	0.3(0.4)	0.3(0)			0.4(0.6)	26.81
37	4.188		0.5(0.5)			0.5(0.5)	23.63
38	10.575		0.6(0)			0.4(1)	22.6
39	6.322		0.2(0)			0.8(1)	26.69
42	4.47		0.2(0)			0.8(1)	26.69
43	9.968	0.1(0.1)	0.5(0)			0.4(0.9)	24.01
45	1.643	0.5(0.5)				0.5(0.5)	30.64
47	6.909	0.2(0.5)	0.5(0)			0.3(0.5)	24.39
49	8.748		1(1)				18.52
50	11.267	0.2(0.5)	0.7(0.5)			0.1(0)	22.35
52	7.673	0.3(0.5)	0.4(0)			0.3(0.5)	19.76
54	4.147	0.8(0.8)				0.2(0.2)	31.79
56	13.594	0.2(0.5)	0.4(0)			0.4(0.5)	25.41
58	0.378	1(1)					32.55
60	22.874	0.4(0.5)	0.3(0.1)			0.4(0.4)	27.33
64	5.449	0.8(1)				0.2(0)	29.74
65	2.753		1(1)				18.52
66	17.86	0.2(0)	0.8(1)				21.33
69	12.826	0.5(1)	0.2(0)			0.3(0)	28.6
70	10.425	0.4(0.7)	0.3(0)			0.3(0.3)	27.2
71	1.147		0.8(1)				18.52
74	3.414		0.9(1)				18.52
80	5.492	0.8(0.8)				0.2(0.2)	31.79
81	2.883	0.6(0.8)	0.4(0.2)				26.94
82	16.042	0.2(0.5)	0.8(0.5)				21.33
84	9.195	0.2(0.5)	0.8(0.5)				21.33



Sub-watershed	Area(mi ²)	Precipitation Gage Depth (Time) Weights					42-hr Rainfall (in)
		HI81	HI83	HI91	HI92	HI94	
89	8.656		0.85(1)				18.52
93	8.862	0.4(0.5)	0.2(0.3)			0.4(0.2)	27.39
96	1.456	0(0.2)	1(0.8)				18.52
99	7.239	0.5(0.5)			0.5(0.5)		31.77
102	3.132	0.9(0.8)	0.1(0.2)				31.15
108	3.979	0.2(0.2)	0.3(0.3)		0.5(0.5)		27.56
110	3.428	0.1(0.1)	0.6(0.6)		0.3(0.3)		23.66
112	5.449		0.6(0.5)		0.4(0.5)		23.5
115	9.23		0.5(0.2)		0.5(0.8)		24.75
117	8.502		0.5(0.1)	0.2(0.3)	0.3(0.6)		23.81

Table 3 - 9. Comparison of Model Results for November 1 to 2, 2000, Storm.

Junctions	Description	Drainage Area (mi ²)	HEC-HMS (cfs)	FLO-2D (cfs)
J2	Volcano Rd & Kahaualeale Rd	22.90	12,717	12,215
J3	Near Mauaana Rd	43.66*	23,983	23,087
J4	Near 'Āpele Rd	52.21*	21,215	22,803
J5	South Kūlani Rd Bridge	78.00*	30,386	32,402
J7	Kea'au-Pāhoa Rd & Keaau Bypass Rd	109.63*	22,449	24,019
J8	Volcano Rd & Huina Rd	23.25	8,786	9,875
J10	Railroad Ave. & Kea'au Rd	16.10	2,993	2,725
JK1	Pulelehua Rd & Poola Rd	28.32	3,554	3,496

*The Marked Drainage Area is the area without considering the topographic diversion.



3.8 Hydrologic Analysis Results

After the calibration, the next step is to select the final model parameters for the storm frequency computations. For the reason that there is only one calibration event, the November 1 to 2, 2000 storm, it's difficult to assess an accurate prediction basin model for future storms. The final basin models were compared with FLO-2D model results and to optimize the model using FLO-2D model results as referenced observed flows. The HEC-HMS parameters were checked to make sure they are in a reasonable range. Table 3-10 gives the HEC-HMS model results for the four designed storm events at the selected nine junctions.

Table 3 - 10. Puna Study Area HEC-HMS Results

Junctions	Description	Drainage Area (mi ²)	10-year (10% Annual Chance) (cfs)	50-year (2% Annual Chance) (cfs)	100-year (1% Annual Chance) (cfs)	500-year (0.2% Annual Chance) (cfs)
J2	Volcano Rd & Kahaualeale Rd	22.90	9,454	23,955	35,157	46,240
J3	Near Mauaana Rd	43.66	19,063	40,749	59,984	80,339
J4	Near 'Āpele Rd	52.21	19,538	36,533	45,384	61,031
J5	South Kūlani Rd Bridge	78.00	25,024	45,398	61,326	84,906
J7	Kea'au-Pāhoa Rd & Keaau Bypass Rd	109.63	15,187	30,993	40,720	63,826
J8	Volcano Rd & Huina Rd	23.25	5,859	12,212	17,055	25,270
J10	Railroad Ave. & Kea'au Rd	16.10	1,361	3,916	5,539	11,894
JK1	Pulelehua Rd & Poola Rd	28.32	1,229	8,197	17,854	28,551
J16	Volcano Rd & Kahaualeale Rd	10.14	241	1,035	2,672	8,712



The HEC-HMS model results were compared with the FLO-2D model results (Appendix A). Table 3-11 gives the comparison of the peak discharges at the nine conjunctions for the four storm events. The HEC-HMS results are comparative and match closely with the FLO-2D results. The differences between the two models at the major junctions are within 15%. Based on this comparison, HEC-HMS model results provide sufficient estimations for the four storm events. The hydrologic results of HEC-HMS model are applicably accurate to use as input to the FLO-2D model in hydraulic analysis.

Table 3 - 11. Peak Discharge for Storm Events

Junctions	Description	10- Year (10% Annual Chance)		50- Year (2% Annual Chance)		100- Year (1% Annual Chance)		500- Year (0.2% Annual Chance)	
		cfs		cfs		cfs		cfs	
		HEC- HMS	FLO- 2D	HEC- HMS	FLO- 2D	HEC- HMS	FLO- 2D	HEC- HMS	FLO- 2D
J2	Volcano Rd & Kahaualeale Rd	9,454	9,596	23,955	22,330	35,157	33,418	46,240	46,266
J3	Near Mauaana Rd	19,063	17,648	40,749	36,532	59,984	54,024	80,339	74,770
J4	Near Apele Rd	19,538	17,410	36,533	31,291	45,384	44,008	61,031	63,610
J5	South Kūlani Rd Bridge	25,024	20,684	45,398	39,041	61,326	51,602	84,906	75,217
J7	Keaau- Pahoa Rd & Keaau Bypass Rd	15,187	14,734	30,993	31,463	40,720	40,507	63,826	59,910
J8	Volcano Rd & Huina Rd	5,859	6,017	12,212	13,046	17,055	16,191	25,270	24,023
J10	Railroad Aves. & Keaau Rd	1,361	1,248	3,916	3,684	5,539	5,640	11,894	11,935
JK1	Pulelehua Rd & Poola Rd	1,229	777	8,197	7,360	17,854	16,165	28,551	29,194
J16	Waimakao Pele Rd & Pahoche Rd	241	171	1,035	1,080	2,672	2,608	8,712	8,581



4 HYDRAULIC ANALYSIS

4.1 FLO-2D Model Overview

The terrain of the Puna area is characterized by broad and gentle slopes. The land surface consists of porous volcanic rock and soils from Mauna Loa and Kilauea eruptions. There are no well-defined waterways within the project area. There is an extensive network of subterranean lava tubes throughout much of this area. For this reason, a two dimensional hydraulic model such as FLO-2D would have advantage over one dimensional model such as HEC-RAS. FLO-2D model was selected to conduct the hydraulic analysis of the complex two-dimensional flood flows in the Puna area.

FLO-2D is one of FEMA's approved hydraulic models for both riverine and unconfined alluvial fan flood studies. FLO-2D simulates flood wave attenuation and predicts the area of inundation by numerically solving the continuity equation and the dynamic wave momentum equations on a grid system. As a two-dimensional model, FLO-2D distributes the rainfall and runoff based on the terrain information on each grid and provides more accurate representation of overland flow. FLO-2D does not distinguish subcritical and supercritical flow and so it doesn't have restrictions when computing the transition between the flow regimes. The model has the capability to include many parameters such as the rainfall, infiltration, ground surface roughness, levees, and hydraulic structures.

4.2 FLO-2D Model Setup

4.2.1 Topographic Database

The topographic data has an average point spacing of 8 feet. The Digital Terrain Model (DTM) data for Puna Watershed was formed with a re-sampling resolution of 16 feet by 16 feet to reduce the data file size. A 300-foot-grid-size model for the whole study area was preliminarily tested to determine general trends of the floods before the final 128-foot grid models were fully developed. The re-sampled data was used to build the FLO-2D model using a 128' x 128' grid cell size. This grid cell size was recognized by county of Hawaii, Department of Public Works. Each grid element contained an average of 64 elevation points (DTM data with resolution of 16' x 16') from which the grid elevations were determined. As suggested by the FEMA's *Guidelines and Specifications for Flood Hazard Mapping Partners*-Appendix C, the selection of the cell size should not only consider the accuracy of the topographic data, but also the computational efficiency of the model and mapping and floodplain management needs. "Too small a cell size not only slows computations, but also creates too many elevation grids, which may not practically be presented on the floodplain map."

For significant structures, such as the South Kūlani Flood Diversion Structure, and the major bridges and culverts, the field survey data was used to better define the elevation and dimensions of these structure. All elevation data utilized was converted and referred to North American Horizontal Datum of 1983 (NAD-1983-HARN-StatePlane-Hawaii-1-FIPS-5101-Feet). The Vertical Datum is based on Local Tidal Level.



4.2.2 Sub-domains and Grid Size

In the hydraulics analysis, five sub-domains were developed, subdividing the whole study area into operable sizes for computational purposes in the FLO-2D models. These five sub-domains were designated as North, Middle North, Middle South, Middle East, and South sub-study areas (See Figure 4-1). These computational sub-domains built up five FLO-2D models. North and South models are individual models for two independent watersheds. The Middle North, Middle South and Middle East models needed the hydrograph input from the upstream basins, so they have to be executed sequentially in the order from Middle South to Middle North and to Middle East. As shown in Figure 3-1, a total of 39 sub-watersheds were delineated across the five model sub-domains. The Northern sub-domain has three separate sub-watersheds (112, 115, and 117), which discharge directly to the Pacific Ocean. The South sub-domain includes sub-watersheds 34, 35, 49, 50, 65, 66, 71, 74, and 89. The Middle sub-domains are comprised of 27 sub-watersheds with a total area of 191.3 mi².

The 128 feet by 128 feet grid size were selected for all sub-domains. Tests indicated the grid element size of 128 feet had already provided sufficient resolution for large flood events. These final models have altogether about 0.5 million grid elements and a substantial long run time.

4.2.3 Hydrologic Input

The methodology used to develop the flood hydrographs for 10, 50, 100, and 500 return years for the Puna study area were described in Section 3 Hydrologic Analysis. In this hydraulic analysis, hydrographs from each sub-watershed were input as inflow sources assigned to specific individual FLO-2D model grid. Figure 4-2 shows the input locations of the hydrograph inflow for FLO-2D models. The hydrologic mode of FLO-2D model was run first (also see Appendix A) to determine the flow paths and the floodplains. Based on the initial test, the input locations of hydrograph inflows were selected along the flow concentration point (normally at the upstream of the major flow path) to provide a conservative predict. A steady state inflow condition was considered for each sub-watershed by keeping the inflow hydrographs at their peak values after the inflow hydrographs reach the peak. The use of steady state condition removes the timing influence on peak discharges and eliminates the attenuation of peak discharges due to volume storage within the floodplain. This method was used in other hydraulic analysis projects such as the “Upper Goose Creek and Two-mile Canyon Creek Flood Mapping Study Update” (City of Boulder Public Works Department, 2012). This approach was taken to meet applicable Federal Emergency Management Agency (FEMA). Figure 4-3 shows the difference between the original hydrograph and the steady state hydrograph at sub-watershed 29 as a typical example. Through the trial and error test, the sub-watersheds at the north sub-domain do not have flooding problem. So the inflow hydrographs for these sub-watersheds are disregarded.

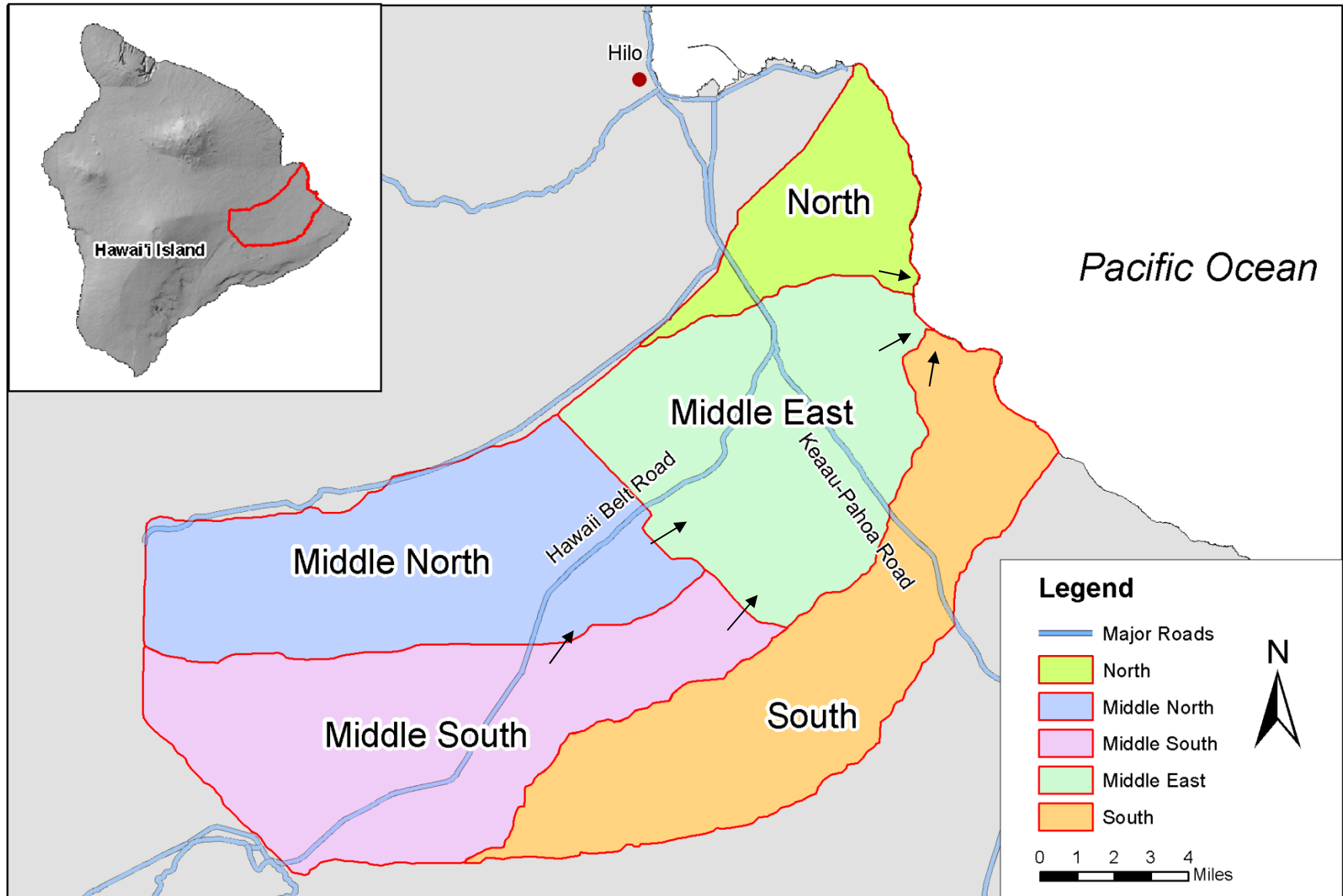


Figure 4 - 1 FLO-2D Model Sub-domains

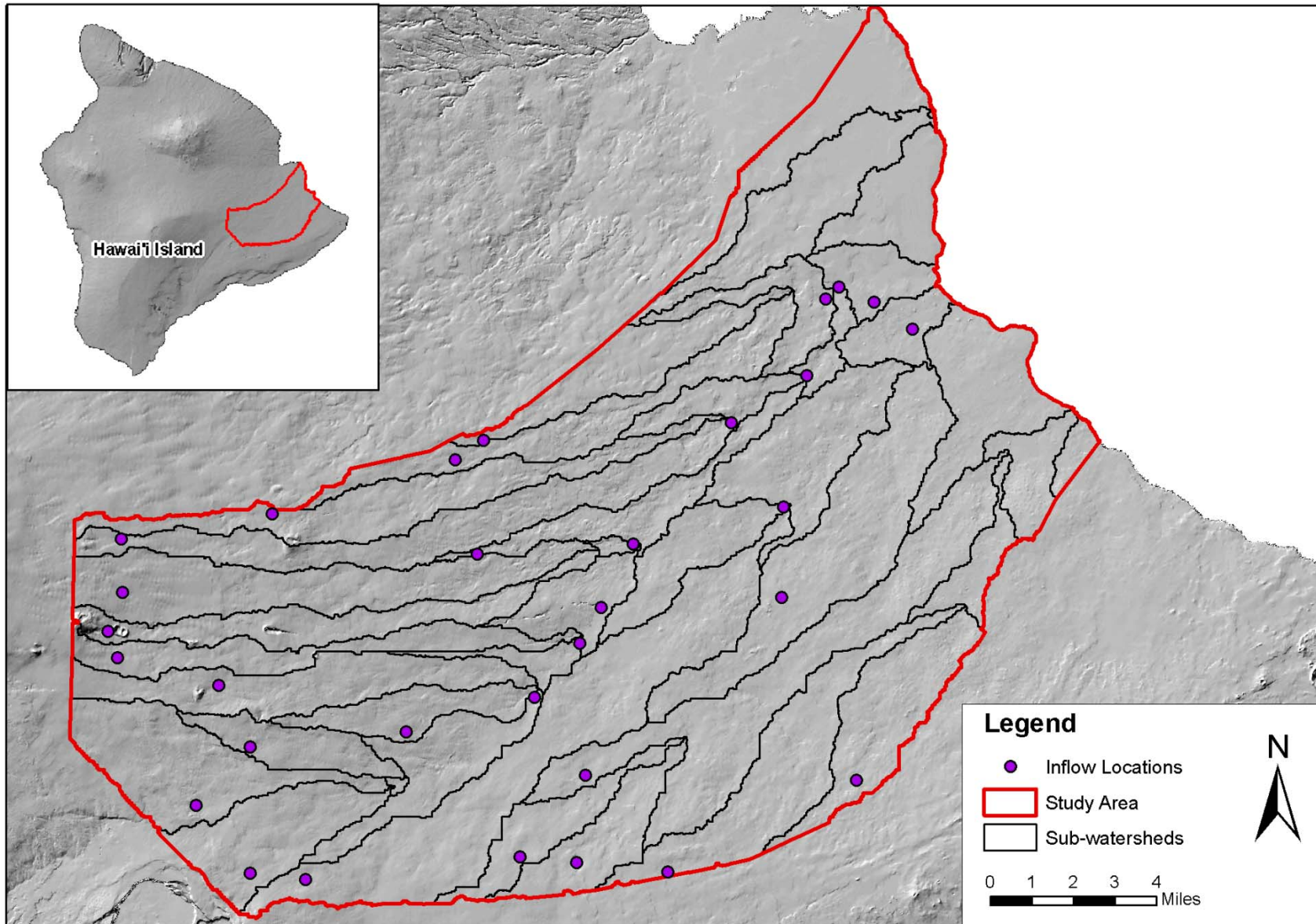


Figure 4 - 2 Hydrograph Inflow locations for the sub-watersheds.

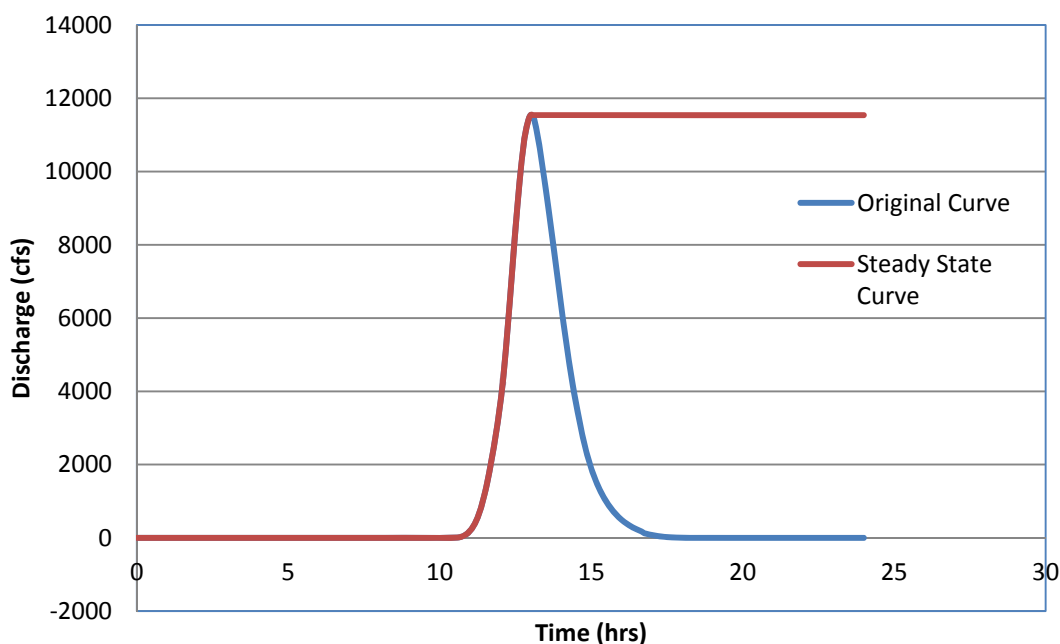


Figure 4 - 3. Typical Steady State Inflow Hydrographs.

4.2.4 Streams

Puna area is composed of recent lava flows. Currently there are no well-defined stream channels in this area because of the slow development of the soil mantle. The terrain in Puna is characterized by broad and gentle slopes, and an extensive network of subterranean lava tubes that runs throughout much of this study area. For these reasons, unconfined flows commonly occurred this area. Shallow stream channel and braided channels have been developed alternatively. Figure 4-4 shows the stream centerline position from Hawaii State Geographic Information System (<http://hawaii.gov/dbedt/gis/>) with the LiDAR data as the background image. From the comparison, the stream channel can hardly be identified from the LiDAR data in most of the stream locations. At some locations, the stream channel seems to have wandered and relocated. During the field survey, the stream channel is also not identifiable at some locations. Pictures were taken during one field visiting as marked by the numbers 1 through 4 in Figure 4-4. Figure 4-5 through 4-8 show the pictures taken at those locations. At some locations, where the streams cross the road, the road only show wavy geomorphologic features with no typical features for a stream channel such as the stream bed or stream banks. The stream behaves like overland flow at some places as shown in Figure 4-8. Combining all these observations, we can assess the Kea'au stream is not a well-defined stream. Therefore in this hydraulic study, streams are not simulated as the one-dimensional channels. The FLO-2D model simulates the streams as floodplain flow with proper manning's n values. Stream water surface elevation is extracted from the floodplain water surface elevation along the stream centerline.

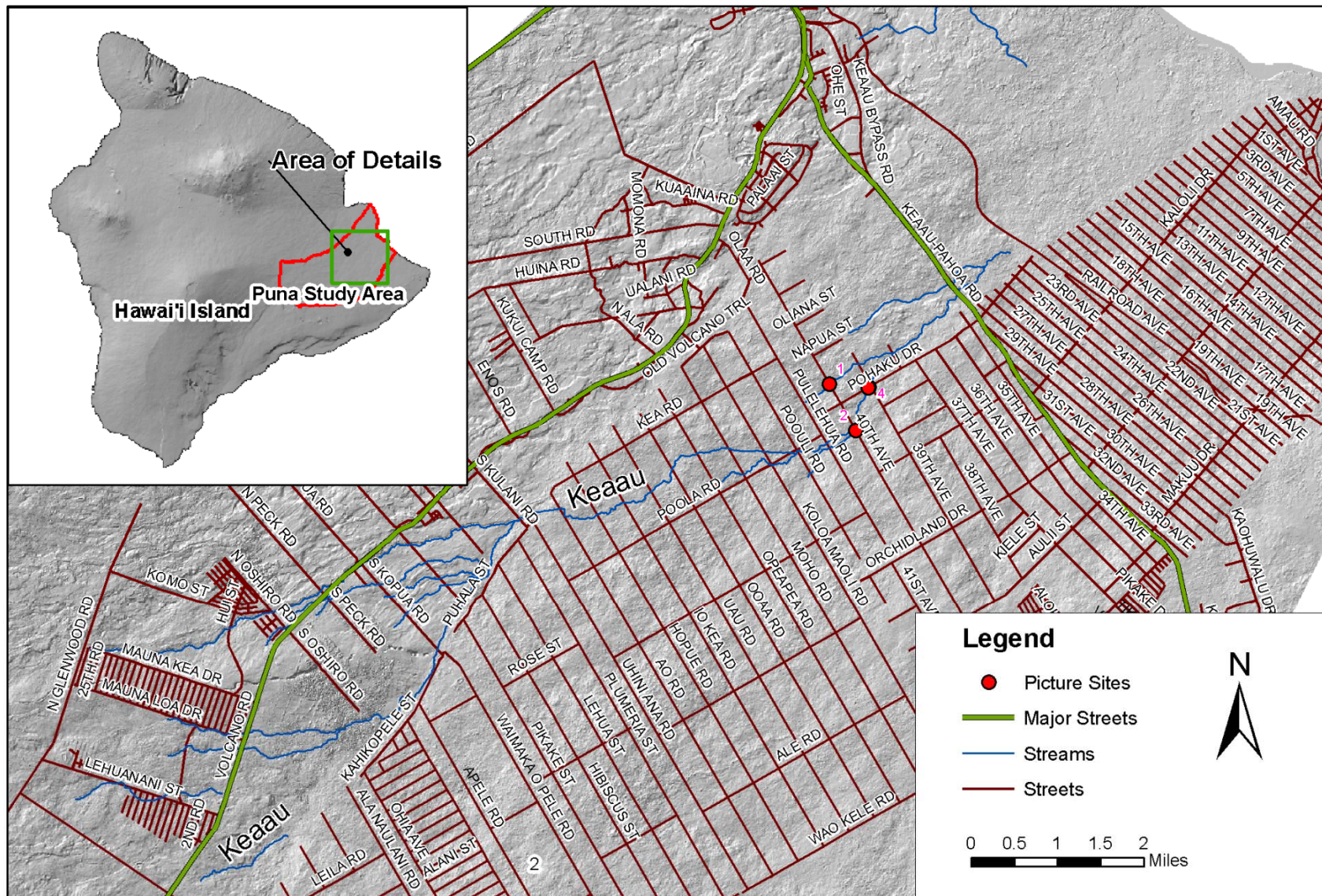


Figure 4 - 4 Keaau Stream locations from Hawaii State Geographic Information System



Figure 4 - 5 40th Avenue at 1400 Feet North of the Intersection with Pohuku Drive



Figure 4 - 6 40th Avenue at 1800 Feet South of the Intersection with Pohuku Drive



Figure 4 - 7 The Intersection between the 39th Avenue and Pohaku Drive



Figure 4 - 8 Keaau Stream before Crossing the Intersection between the 39th Avenue and Pohaku Drive



4.2.5 Water Diversion Systems

The South Kūlani diversion system is a water diversion structure, which extends over one half mile in length. According to the recollections of the local residents, the walls were built by ‘Ōla’a Sugar Company in 1938, to divert floodwater away from cane fields along the Mauna Loa/Kilauea boundary into what was then called “wasteland”, owned by W.H. Shipman (County of Hawai‘i, Department of Planning 1995). In 1958, the “wasteland” was developed as a subdivision, now called Hawaiian Acres. Many local people living there are unaware of the flooding problems.

Hawaiian Acres Community Association (HACA) has tried to make the local residents aware of the potential of flood hazards at the Hawaiian Acres. HACA provided a brief map to describe the possible flood path down the South Kūlani Bridge as shown in Figure 4-9 (Figure from <http://www.hawaiianacres.org/history.shtml>). This map provided the approximate structure location while giving an impression that there is a floodwall downstream the South Kūlani Bridge which blocked the initial main watercourse to divert the water to the Hawaiian Acres. Since this “floodwall” was not picked up in the LiDAR data, Oceanit conducted land survey to locate this “floodwall”. The structure was surveyed in October, 2011 and the results did not match with the HACA sketch. The diversion system composed of a flow split made of a V-shape dike and a series of guiding walls made of cemented rocks. A plan view of the whole structure layout is shown in Figure 4-10 (Notice: the map is rotated to give an easy comparison with Figure 4-9). The blue lines in the figure show the existing structures with the slopes indicated in front of them at some locations. Appendix B provides a detailed analysis of the surveyed structure profile. The survey data and the LiDAR data generally show similar confinement effects on flow since the crest elevation of the rock wall is not higher than the landward ground elevation in most of the sections. The survey results turn out be similar with the LiDAR data with only few cross-sections more pronounced than the LiDAR data.

Figures 4-11 through 4-12 show the current situations of the cemented rock wall. Trees and dense vegetation grow along the wall. Portion of the wall has collapsed due to the lack of maintenance (Figure 4-12). From the layout of the structure, it seems that the cemented rock walls were used to divert the water to the Hawaiian Acres for small flooding events. Their functionality is a little different from the levee structure. Formerly, FEMA used the without levee approach to assess flood hazards associated with non-accredited levee system. “Under the former approach, when a levee system did not meet the National Flood Insurance Program (NFIP) requirements cited in the Code of Federal Regulations (CFR) at Title 44, Chapter 1, Section 65.10 (44CFR65.10), FEMA analyzed the flood hazards and represented the flood hazards in leveed areas on the Flood Insurance Rate Map (FIRM) as if the levee system does not exist (FEMA 2011)”. FEMA updated the method to model the non-accredited levees in December 9, 2011. The proposed Levee analysis and mapping protocol include several procedures: Sound Reach Procedure, Freeboard Deficient Procedure, Overtopping Procedure, Structural-Based Inundation Procedure and Natural Valley Procedure. The guiding wall in this hydraulic diversion system is not the same as the levee structure. However, sensitivity analysis is still conducted to see the difference between the with-structure and without-structure situation.

The rock walls were built along the south side of the stream bank and were simulated by using the levee component in FLO-2D. The location and top elevation of the wall was input



into the FLO-2D model. The FLO-2D levee component confines flow by blocking one or more of the eight flow directions in each grid element. When the flow depth exceeds the levee height, the discharge over the levee is computed using a broad-crested weir flow equation. From Figure 4-10 or Figure 4-14, a narrow stream channel around 30 feet wide can be seen along the north side of the rock wall footprint. This sub-grid topographic feature cannot be represented by the FLO-2D grid size, so a channel component was added in the FLO-2D model to mimic the topographic restriction on the flow. Based on the survey data and the LiDAR data, this channel feature has a depth in the range of 1 foot to 8.7 feet under the right bank crest elevation.

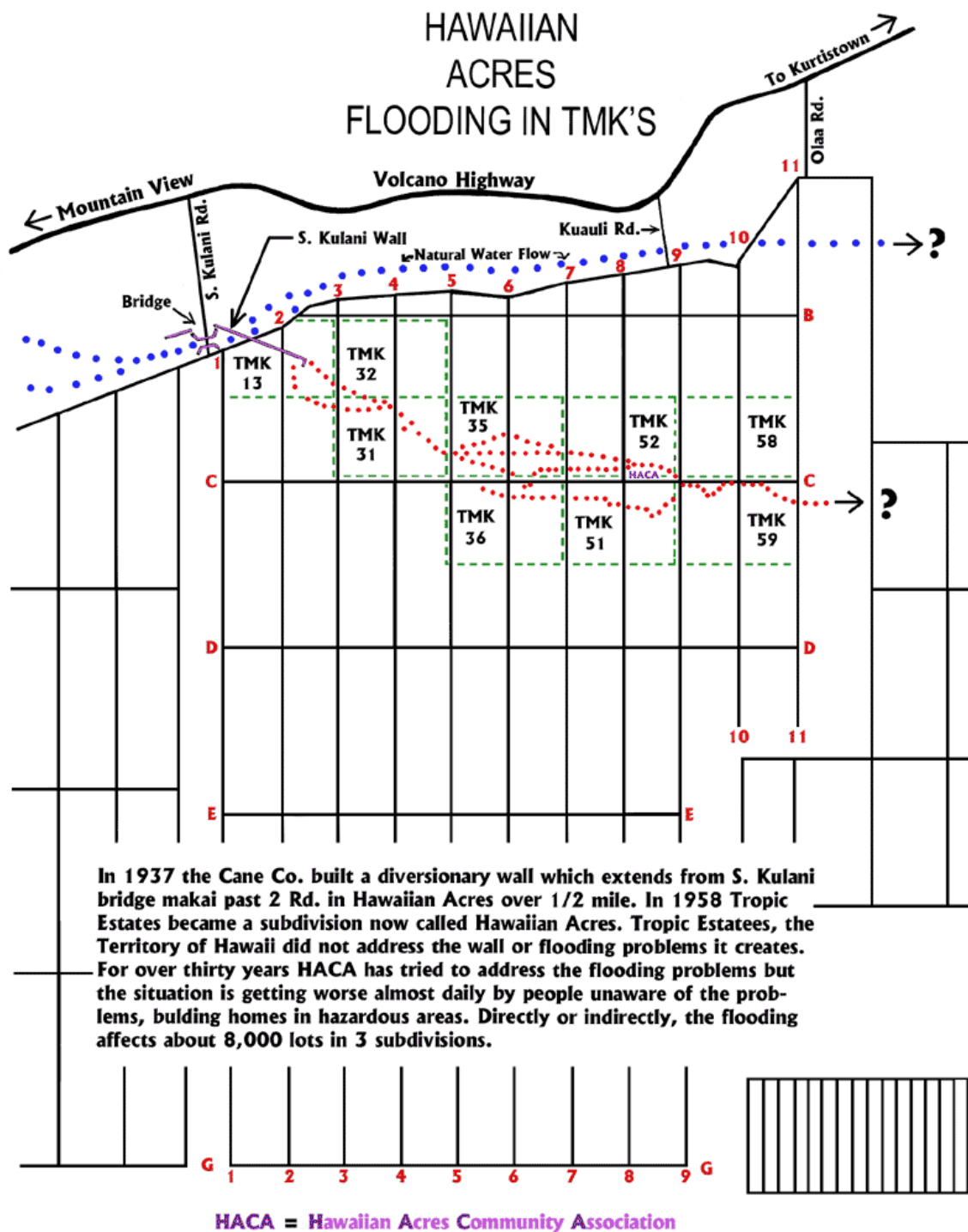


Figure 4 - 9 Potential Flooding Problems at Hawaiian Acres by HACA

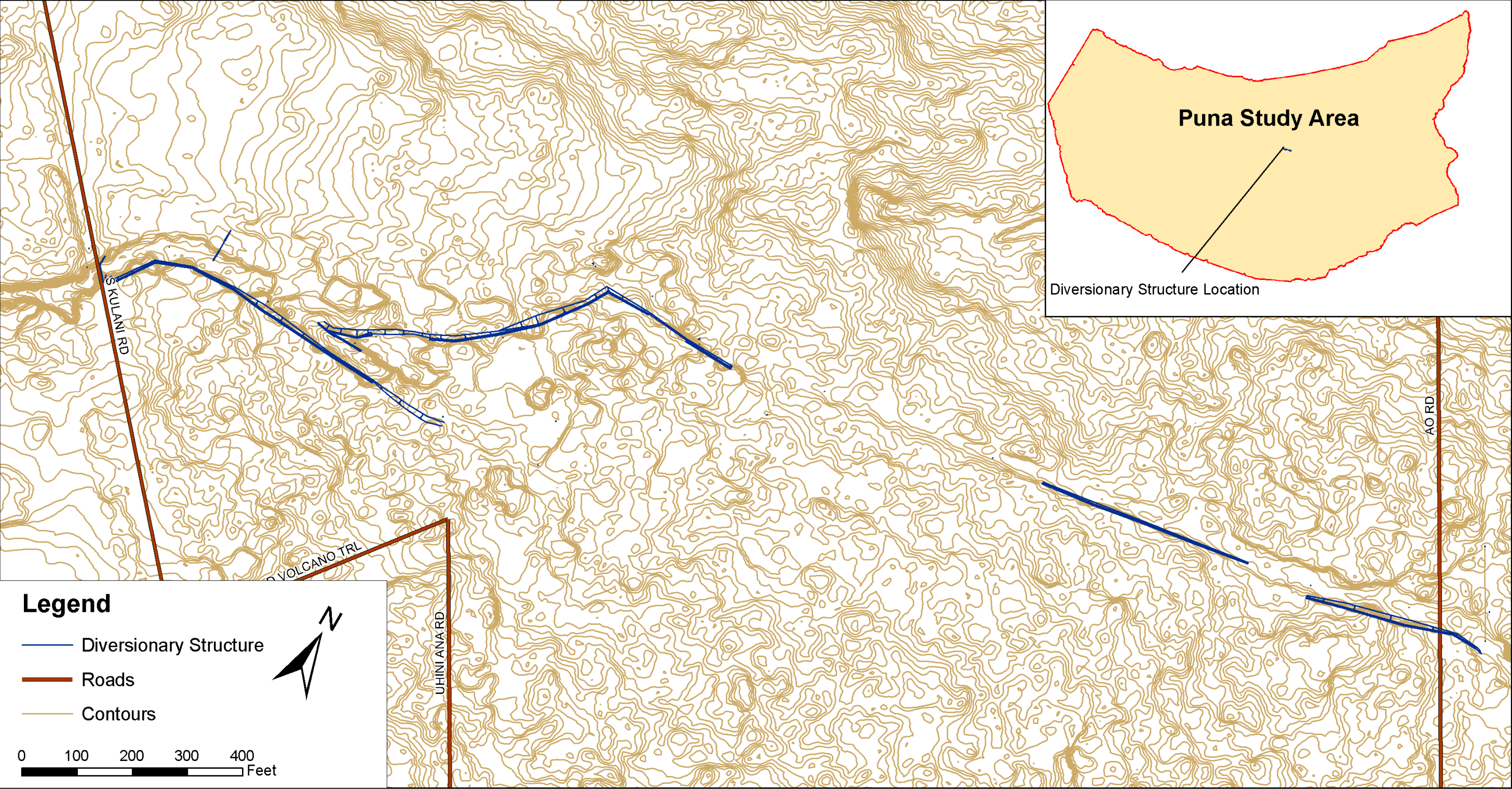


Figure 4 - 10 Diversionary Structure Layout



Figure 4 - 11 Photo of Rock Wall

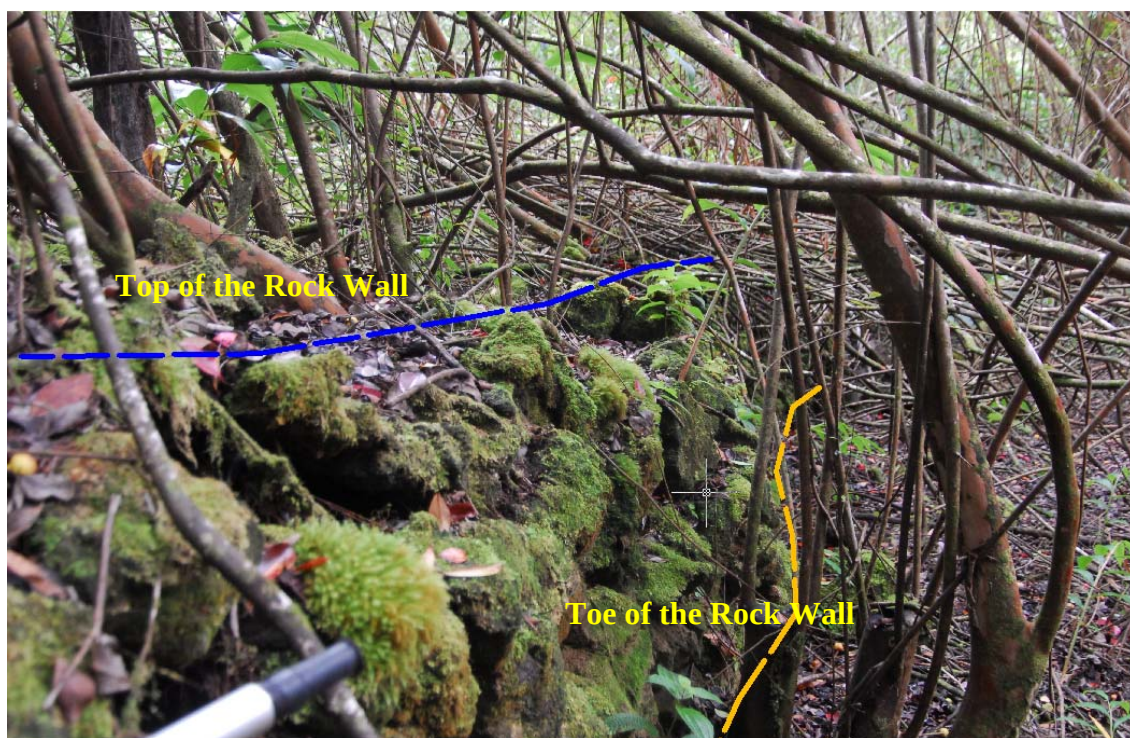


Figure 4 - 12 One Section of the Rock Wall



Figure 4 - 13 Failed Section of Rock Wall

4.2.6 Bridges and Culverts

Bridges and culverts play an important role on the floodplain delineation. The major bridges and culverts within the project area were surveyed by the Oceanit engineers. Based on the analysis of the previous field photos, altogether 12 structures were surveyed including 5 bridges and 7 culverts (Denoted by a number in Figure 4-15). The corresponding names of these bridges and culverts are listed in Table 4-1.

Since FLO-2D cannot directly model bridge or culvert hydraulics, the HEC-RAS model was utilized to provide the discharge-rating curves for the FLO-2D model. LiDAR data in the vicinity of the bridges and culverts were converted to the Triangulated Irregular Network (TIN) data. ArcGIS with HEC-GEORAS were utilized to extract the cross-section data close to the hydraulic structures. These cross-section data provided the geometric input for the HEC-RAS model. The surveyed dimensions of the hydraulic structures were then assigned into the HEC-RAS model by HEC-RAS tools. A series of flow rates were applied to the hydraulic models to achieve the rating curve of water elevation vs. the flow discharge. See Appendix C for the hydraulic structure cross-section information and their rating curves. All culverts less than a 36" diameter were not included in the FLO-2D model, since those culverts would not have sufficient conveyance capacity to impact the results of floodplain delineation for this study. The rating curves were assigned to the specific cells related to the structure locations in FLO-2D to account for the bridge and culvert hydraulics.



Figure 4 - 14 Satellite Image of the Area around the Hydraulic Division System

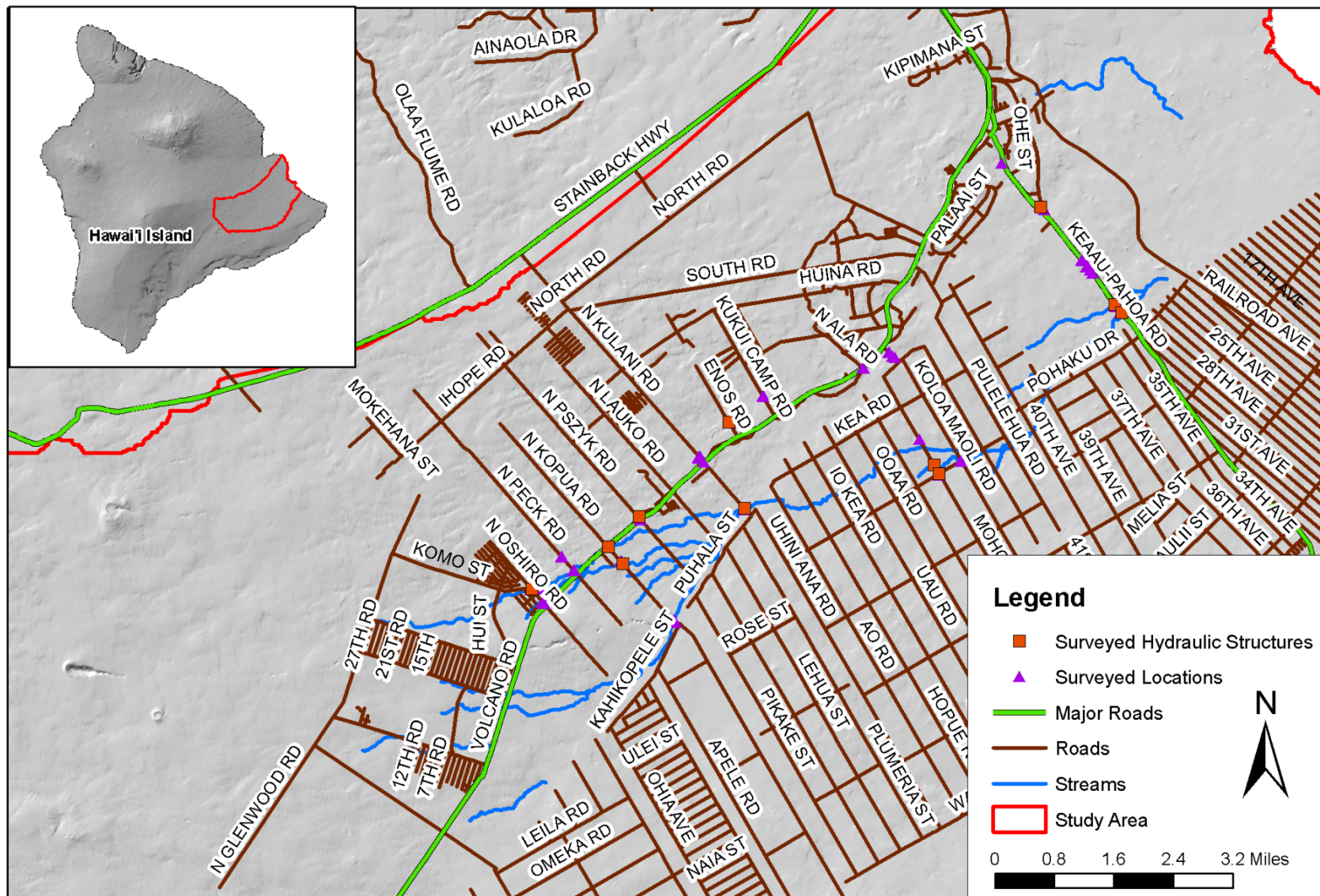


Figure 4 - 15 Surveyed Hydraulic Structure Locations



Table 4 - 1 Names of the Surveyed Bridges and Culverts

No.	Name	Crossing Road Name
1	Keaau-Pahoa Road Culvert 1	Keaau-Pahoa Road
2	Keaau-Pahoa Road Culvert 2	Keaau-Pahoa Road
3	Waipahoe Stream Bridge	Keaau-Pahoa Road
4	Moho Road Culvert 1	Moho Road
5	Moho Road Culvert 2	Moho Road
6	S. Kūlani Road Bridge	S. Lulani Road
7	Enos Road Culvert	Enos Road
8	S. Pszyk Road Culvert 1	S. Pszyk Road
9	S. Pszyk Road Culvert 2	S. Pszyk Road
10	S. Kopua Road Bridge 1	S. Kopua Road
11	S. Kopua Road Bridge 2	S. Kopua Road
12	N. Oshiro Road Bridge 2	N. Oshiro Road

4.3 FLO-2D Model Calibration

The severe flooding event on November 1 to 2, 2000 caused significant damage to the windward side of the Big Island of Hawai'i. In some places, cottages and stretches of paved roads were washed away, and bridges and culverts were washed out from the roads. The FLO-2D model was calibrated using this flood event. The Manning's n values were adjusted to calibrate the model to simulate the historic event. The Manning's n values were kept in the reasonable range of the recommend values in Table 1 of the FLO-2D manual (2009).



4.4 Hydraulic Analysis Results

4.4.1 Water Diversion System Assessment

The influence of the water diversion system on the flooding area downstream the South Kūlanī Road Bridge was analyzed by a with-structure and without-structure method. The FLO-2D results of the with-structure and without-structure situation are presented in Figures 4-16 and 4-17. Figure 4-16 shows the water depth for the 100-year event downstream the South Kūlanī Bridge and Figure 4-17 gives the water surface elevation profiles for these two situations. From the comparison, these two cases provided very similar results. Hence, the LiDAR data alone can represent the rock wall crest height sufficiently in the terrain model requiring no levee component addition in FLO-2D models. As also noted from Appendix B, the crest elevation of the rock wall is close to the landward ground elevation in most sections.

4.4.2 FLO-2D Model Calibration Result

Reliable inundation area maps or reliable water surface elevation records for the November 1 to 2, 2000 flooding event were not available. The calibration of FLO-2D was based on general matches with the sparse observations of that flood event. The flooding situation at the Puna area was reconstructed by combining different sources of records.

A video record from the Flood Hazards Gallery (University of Hawai'i at Hilo, 2003) shows the disastrous flooding scenes during the November 1 to 2, 2000. Figure 4-18 through 4-20 were snapshots from that video. The exact locations for those snapshots are unknown. Figure 18 shows the ponding water on the road at Puna District. Figure 4-19 shows that flood waters washed away one stretch of the road at Hawaiian Acres. In the picture, a truck fell into the breach in the road and strong sheet flow flowed over the road surface. Figure 4-20 shows the flood waters flowing over the Kukui Camp Road. Flood waves can be seen splashing at the courtyard walls of local residents. Flood flow depth in Figure 4-21 replicates these flood situations.

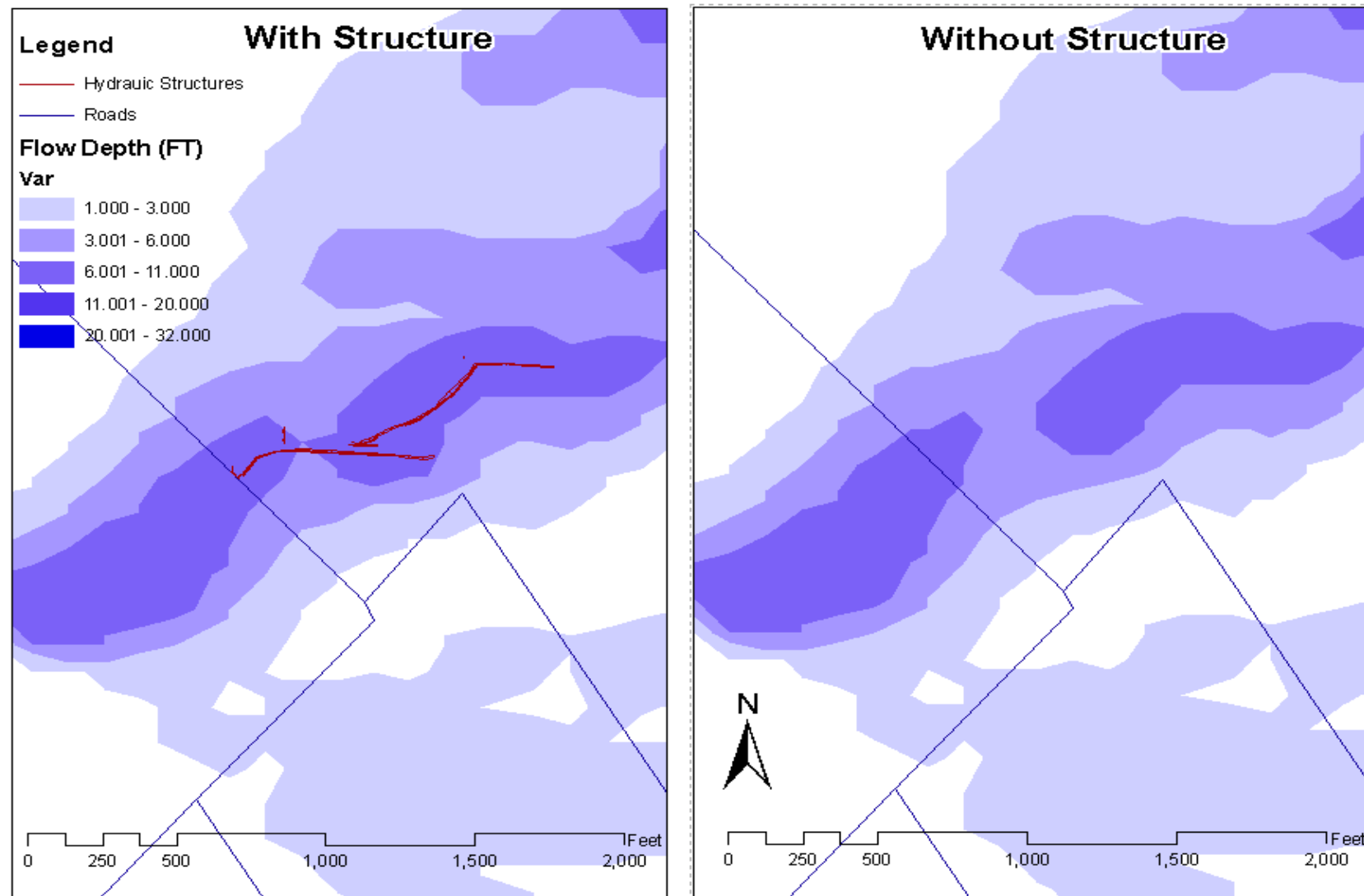


Figure 4 - 16 Comparison of Flow Depth Downstream the South Kūlani Bridge

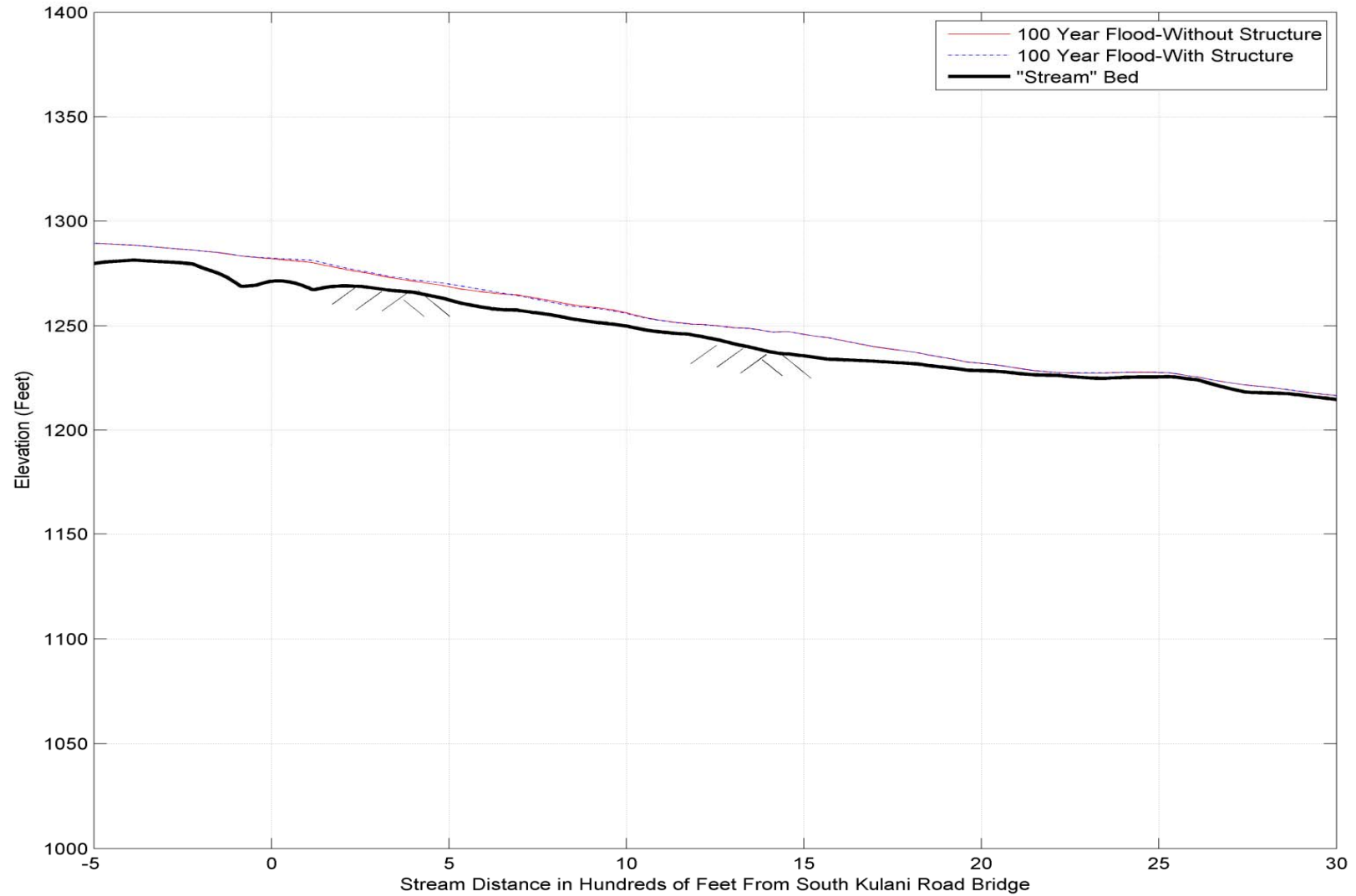


Figure 4 - 17 Flow Surface Elevation in the Case of With - and Without-structure



Oceanit working with the staff from the Highway Maintenance Division Department of Public Works, County of Hawai'i re-visited many flooding locations associated with the flood event. The observed flooding water depth for the November 1 and 2, 2000 event was recalled from the field survey mentioned earlier. Figure 4-21 shows the field visit locations with the flooding map of model result in the background. Table 4-2 lists the observed flooding water depth and the flooding water depth from the model.

Another source for the flooding validation is from the County of Hawai'i Memo (County of Hawai'i, 2001). The Memo mentioned that the stretch of Kuauli Road has been completely washed out in 1986, 1994, and 2000 flood events (Figure 4-22). Figure 4-21 shows a major flood path across the Kuauli Road, which is consistent with the event. Modeling of the road breach is out of the scope of this work.



Figure 4 - 18 Flooded Roads at Puna District



Figure 4 - 19 Flood Waters Wash Away a Stretch of the Road at Hawaiian Acres



Figure 4 - 20 Flood Waters Flow over the Kukui Camp Road



Table 4 - 2 FLO-2D Model Calibration Results for November 1 to 2, 2000 Storm

ID	Locations	Water depth Observed by Highways Maintenance Division	FLO-2D Model Results(Feet)
1	Oshiro Rd bridge 2	About 15 ft at bridge	13
2	N. Peck Rd. Bridge 1	overtopped	0.53
3	N. Peck Rd. Bridge 2	overtopped	2.16
4	Intersection of S. Kopua Rd. and Volcano Rd	overtopped	8.4
5	Intersection of S. Pszyk Rd. and Volcano Rd	6x10 box culvert, 14 ft length, overtopped box culvert	0.3
6	S Kūlani Rd. Bridge	flooding area	5
7	ENOS RD	overtopped, deep water	1.9
8	Kukui Camp Rd	Based on water mark at Kukui Camp Rd., the water depth was about 6-8 ft	2.4
9	Ala Loop. and Volcano Rd	very deep water, 5-10 ft	7.6
10	Kuauili Rd.	about 2 ft	3
11	Moho Rd.	flooding area	0.4
12	Moho Rd., flooding area	flooding area	0.5
13	Moho Rd. and Poola Rd., Flooding Area	flooding area	0.3
14	Hale Pule Loop.	flooding area	0.9
15	Olaa Rd, close to Volcano Rd.	wide flooding area	0.9
16	Kapiki PL	flooding area	0.6
17	Ipuaiwaha St., Deep Water	Deep Water	1.7
18	Between Keaau Pahou Rd. and Keaau Bypass Rd.	flooding area	6.0
19	Kipimana St. and Kalara St., Edge of Pit	Deep lower area at Kipimana St. and Kalara St.	-

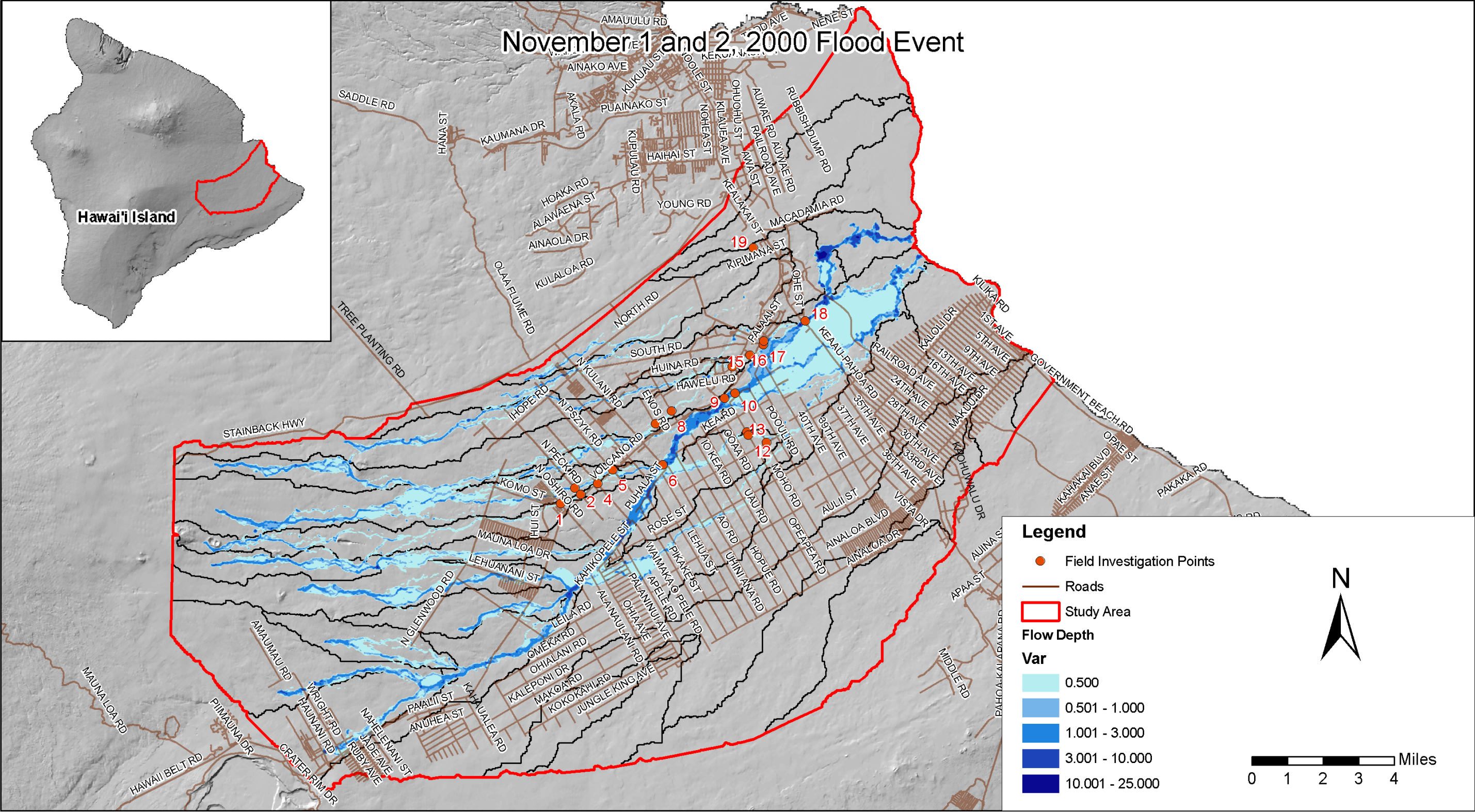


Figure 4 - 21 Field Visit Locations for Storm Event of November 1 to 2, 2000



Figure 4 - 22 Damaged Road Surface at Kuauli Road

4.4.3 FLO-2D Model Results

The North and South sub-domains represent two independent sub-watersheds and there are no inflow hydrographs from upstream watersheds to those sub-models. The term of sub-domain is used instead of sub-watershed since some sub-domain boundary doesn't cover the whole sub-watershed. The Middle South sub-domain doesn't receive boundary inflow and provides outflow to the Middle North sub-domain and the Middle East sub-domain. The Middle North sub-domain receives inflow from the Middle South sub-domain and provides the outflow to the Middle East sub-domain. The Middle East sub-domain receives inflows from both the Middle North and Middle South sub-domains. Figure 4-23 illustrates the boundary outflow cross-section locations for each sub-domain. In this study, the flow hydrographs were obtained at each grid element along the boundary cross-sections and applied to the following elements at downstream sub-domains to consider the variation of inflow along the cross-sections. Since there are over 50 boundary elements involved, for the purpose of clarity only the boundary hydrographs for each cross-section are presented here. The input hydrographs for the downstream sub-domains are listed in Table 4-3.

The flood profiles for the Keaau stream downstream of the South Kūlani Road Bridge were extracted from the FLO-2D model results as shown in Figures 4-24 through 4-27. This reach has a length of about 8 miles and an average stream-bed slope of about 2.5%. From



these flood profiles, the riverine and overland flow alternate features can be verified at some locations. The result also indicates the stream channel is not well-defined.

Figures 4-28 through 4-29 present the maximum water depth for each event. The results for each FLO-2D model run are summarized in the Table 4-4 through 4-7. Volume conservation is the key criteria for the flood routing. It can be seen that the total inflow volume (Inflow hydrograph) and outflow volume (Floodplain outflow, Infiltration and Storage) in these tables match well, which indicates models are accurate and reliable. The maximum inundation area in the table is the area where the minimum water depth is 0.1 foot. The FLO-2D input files, output files, and shape files generated by FLO-2D Mapper tools are submitted as digital files with this report.

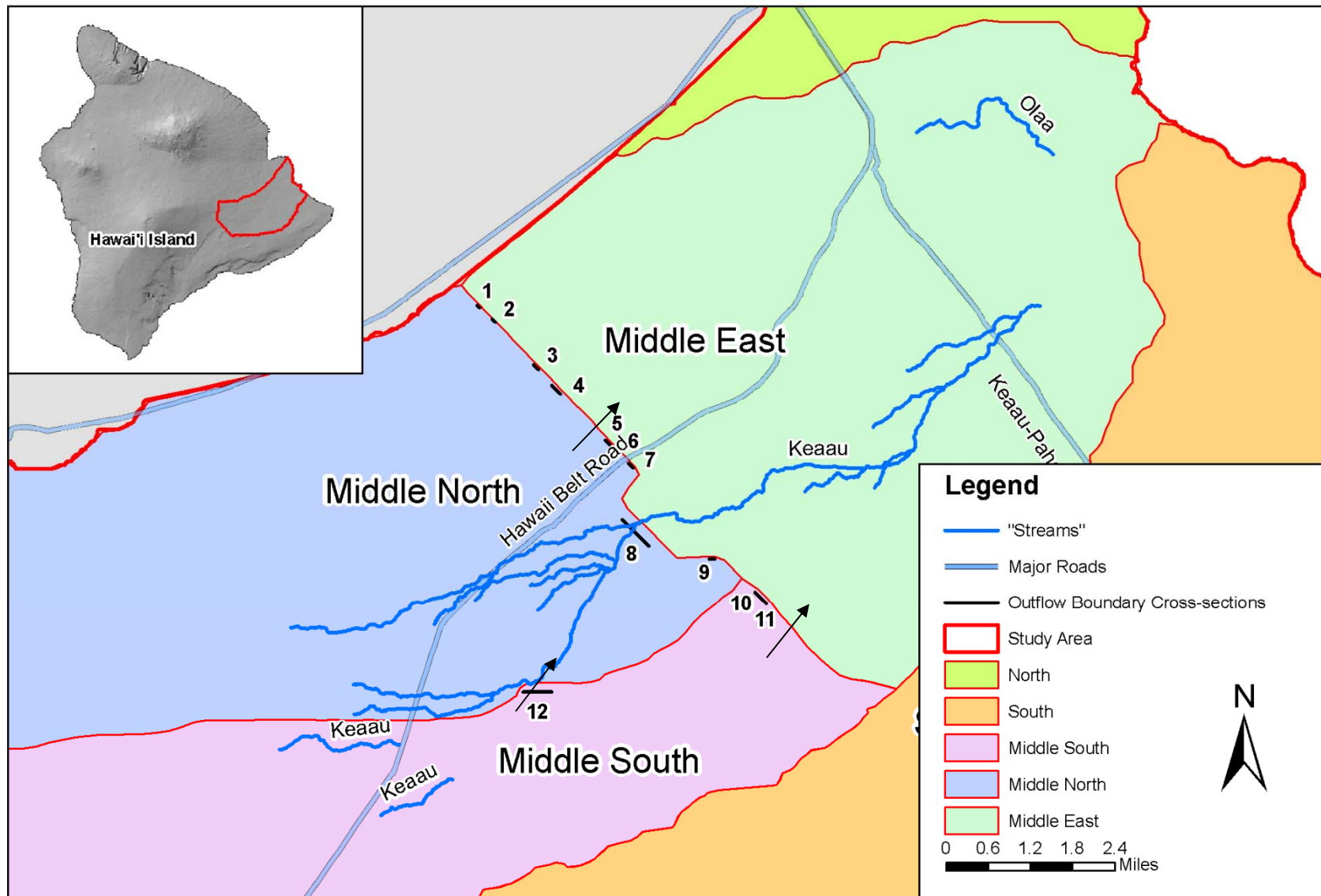


Figure 4 - 23. Outflow Boundary Cross-section Locations.



Table 4 - 3 Boundary Inflow Hydrographs at Cross-sections 1-14 (in cfs)

Boundary Cross-Sections	1	2	3	4	5	6	7	8	9	10
10 Year	773	277	0	912	0	69	30	20,303	0	0
50 Year	1,926	2,158	253	2,366	0	1,443	1,151	45,844	0	2,948
100 Year	3,433	3,553	585	4,126	56	2,010	1,675	55,851	109	6,907
500 Year	4,930	6,809	1,633	6,131	263	3,600	3,492	77,275	452	10,576
Boundary Cross-Sections	11	12								
10 Year	0	12,234								
50 Year	3,418	27,583								
100 Year	6,680	39,297								
500 Year	9,112	51,572								

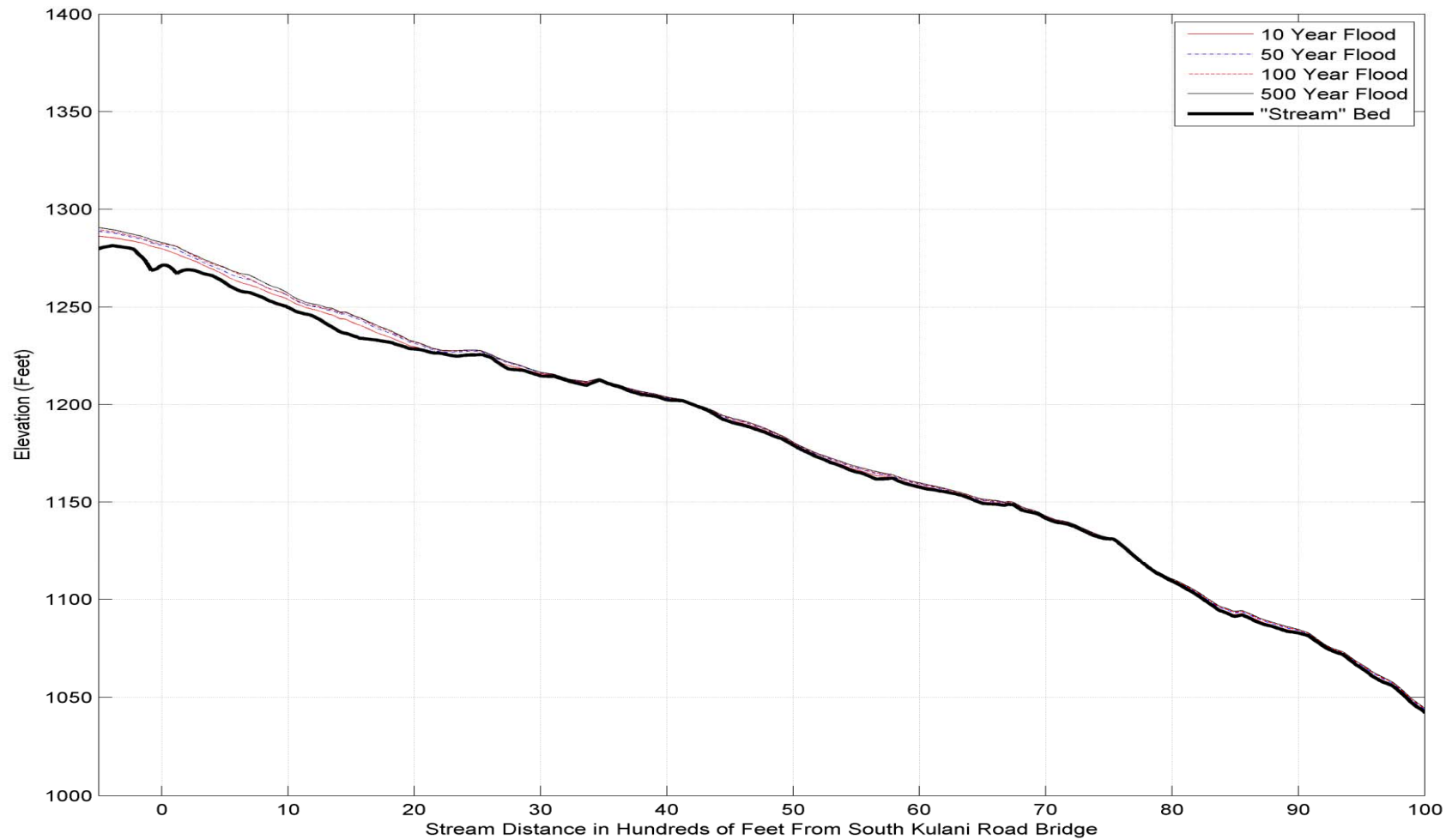


Figure 4 - 24 Flood Profile for Keaau Stream

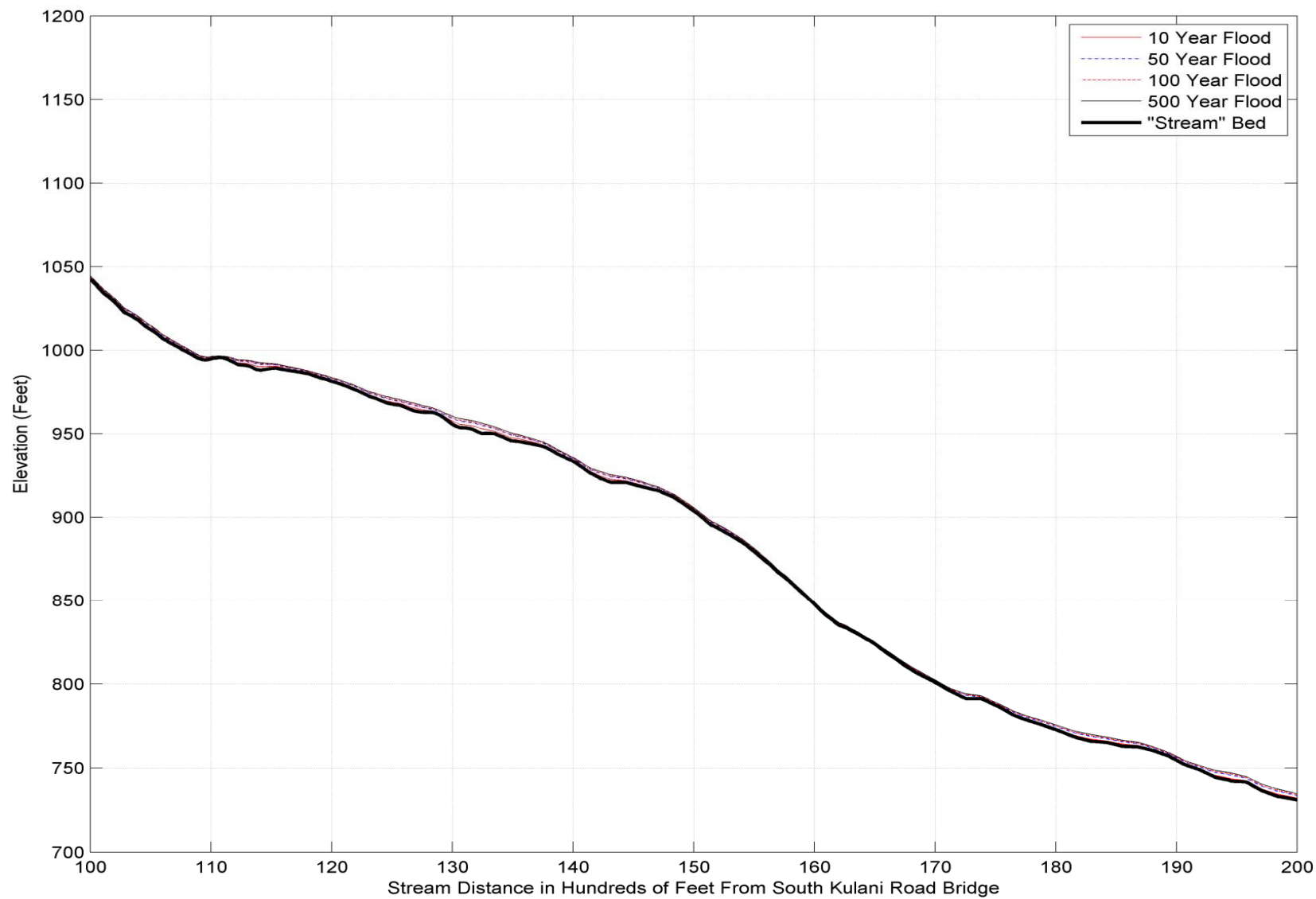
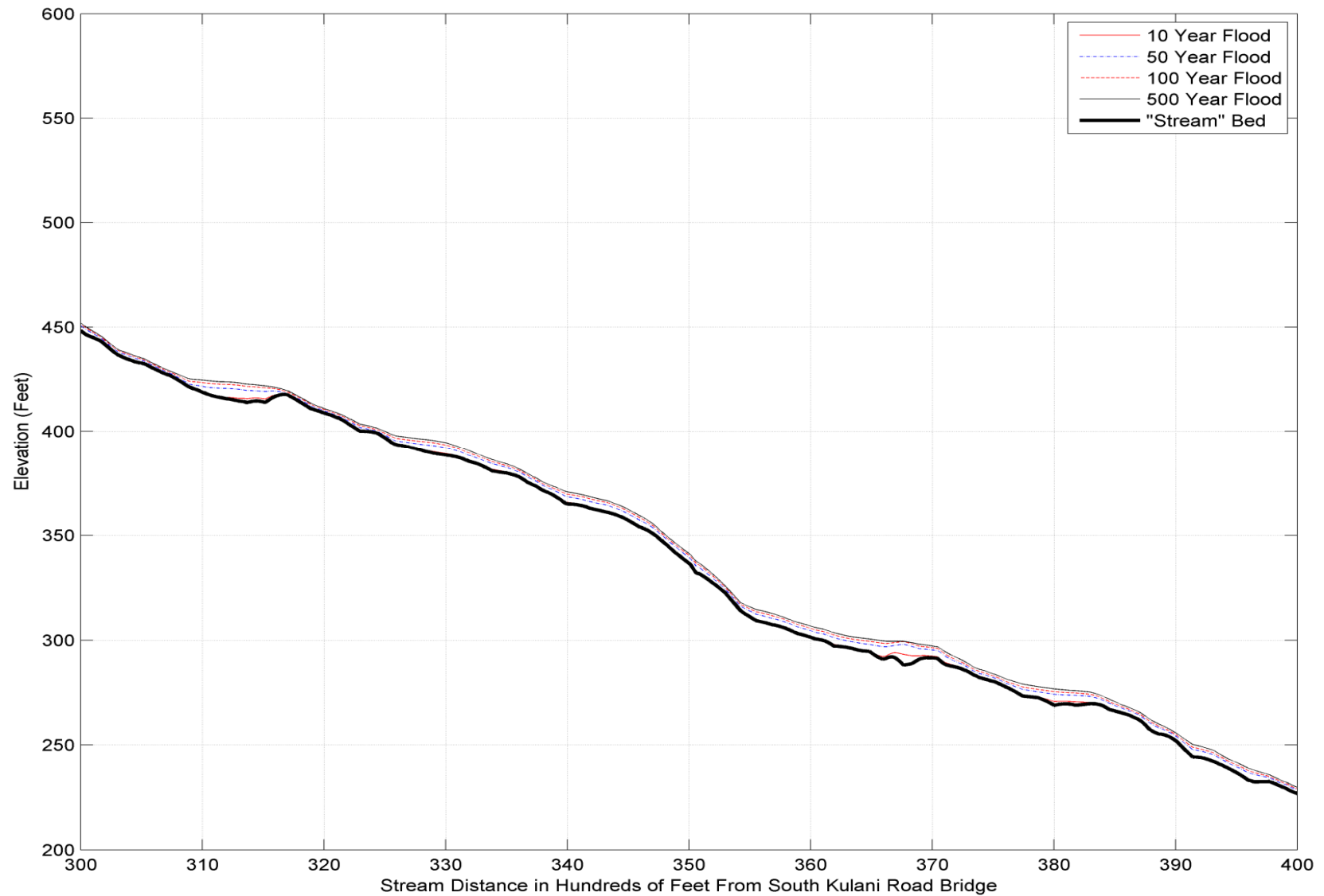


Figure 4 - 25 Flood Profile for Keaau Stream (continued)



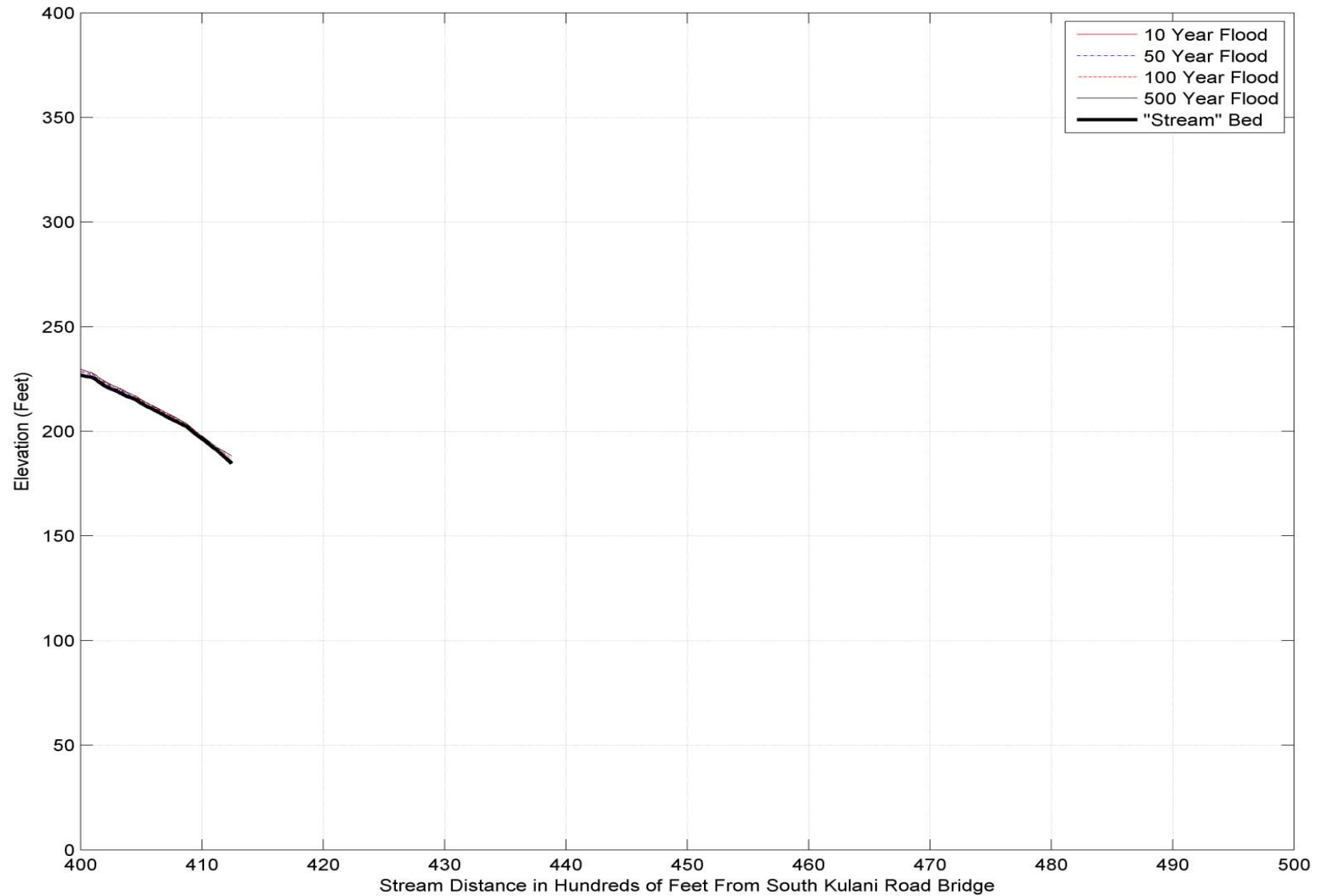


Figure 4 - 27 Flood Profile for Keaau Stream (continued)

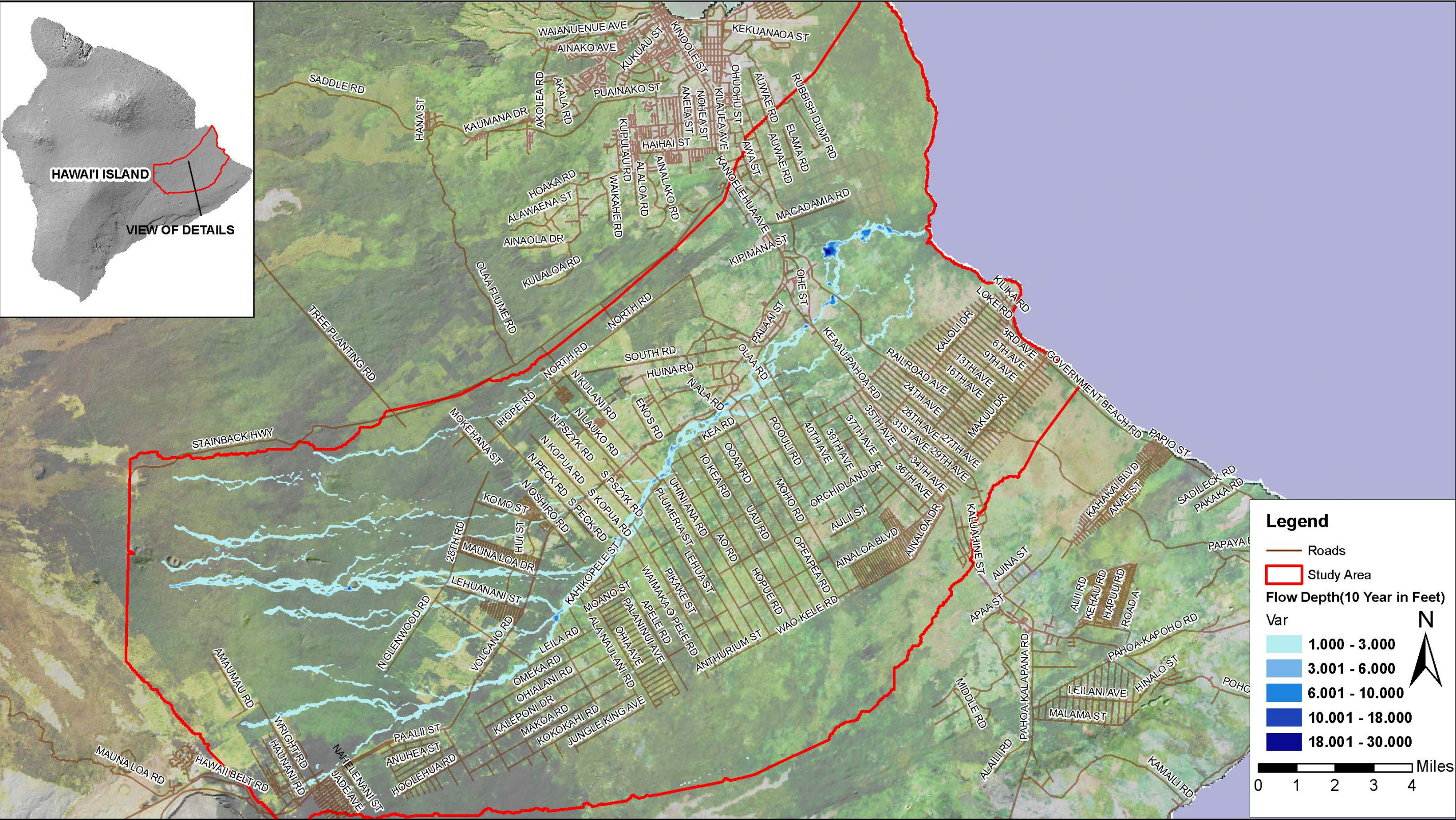
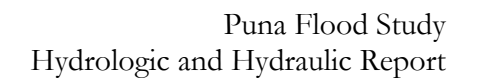


Figure 4 - 28. Flow Depth for 10-Year Flood.



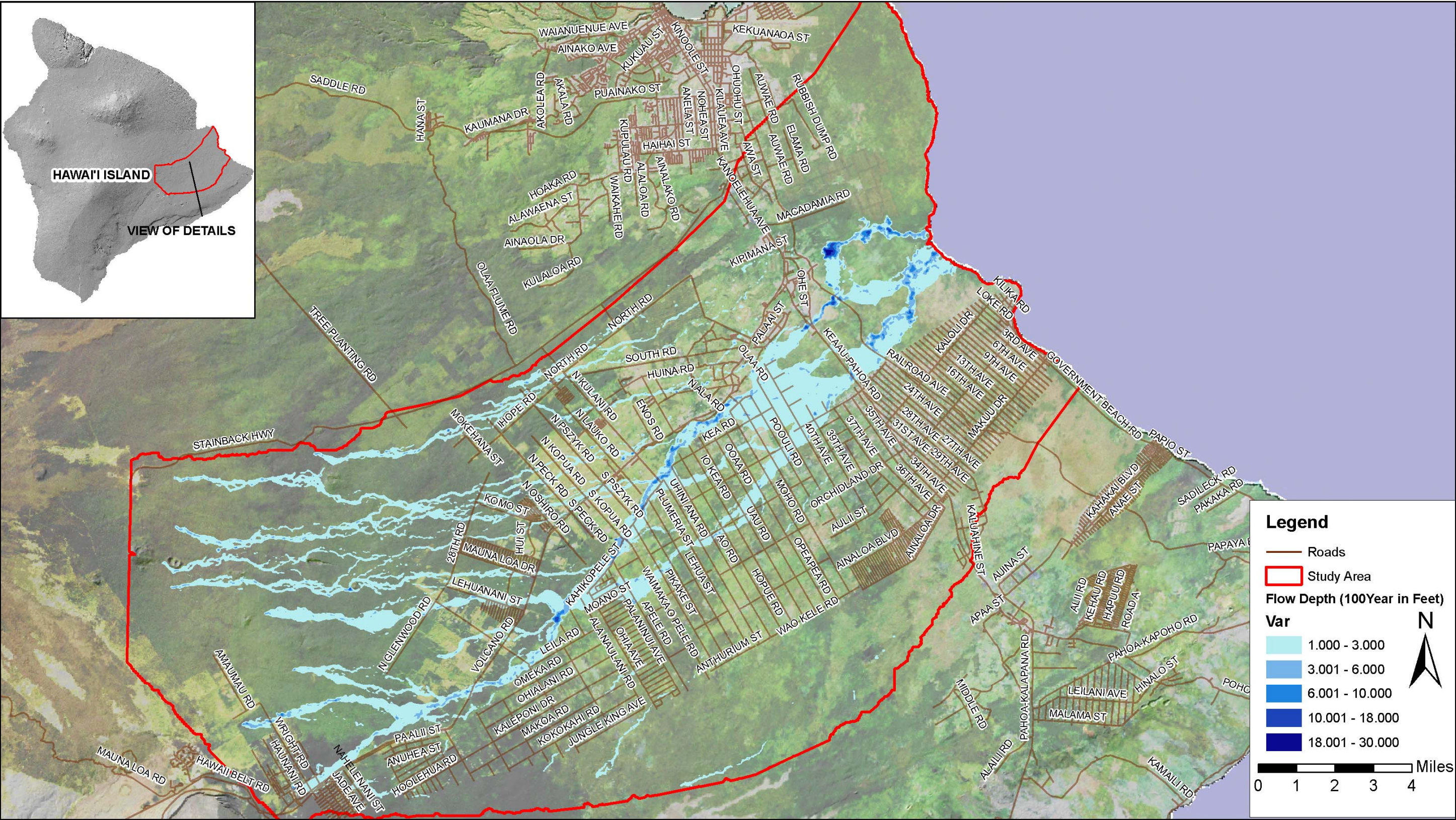


Figure 4 - 30 Flow Depth for 100-Year Flood

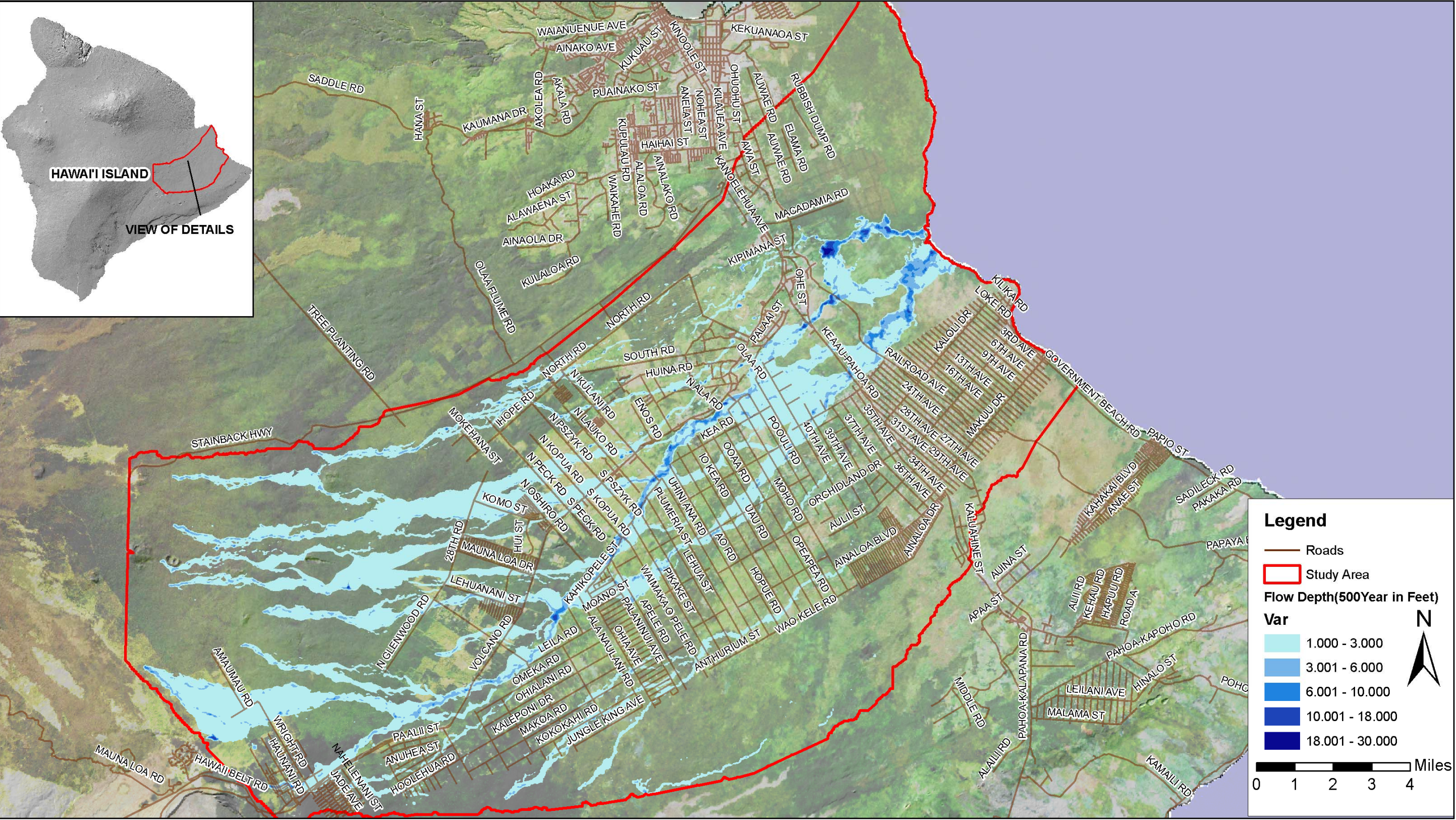


Figure 4 - 31 Flow depth for 500-Year Flood



Table 4 - 4 FLO-2D Model Result Summary for 10-year Flood Event

SUB-DOMAINS:	Middle North	Middle South	Middle East	South
INFLOW:				
INFLOW HYDROGRAPH(ACRE-FEET)	37,044	22,216	14,022	47,758
OUTFLOW:				
WATER LOST TO INFILTRATION & INTERCEPTION(ACRE-FEET)	13,992	8,341	7,099	45,637
FLOODPLAIN STORAGE (ACRE-FEET)	10,623	6,056	6,913	2,059
FLOODPLAIN OUTFLOW HYDROGRAPH (ACRE- FEET)	12,429	7,818	0	62
TOTAL VOLUME OF OUTFLOW AND STORAGE (ACRE- FEET)	37,044	22,216	14,012	47,758
THE MAXIMUM INUNDATED AREA IS(ACRES)	14,987	8,812	5,697	41,251



Table 4 - 5. FLO-2D Model Result Summary for 50-year Flood Event.

SUB-DOMAINS:		Middle North	Middle South	Middle East	South
INFLOW:					
INFLOW HYDROGRAPH(ACRE-FEET)		72,098	48,883	43,148	2,627
OUTFLOW:					
WATER LOST TO INFILTRATION & INTERCEPTION(ACRE-FEET)		19,343	14,057	17,885	2,035
FLOODPLAIN STORAGE (ACRE-FEET)		16,960	11,043	16,941	592
FLOODPLAIN OUTFLOW HYDROGRAPH (ACRE- FEET)		35,795	23,783	8,308	0
TOTAL VOLUME OF OUTFLOW AND STORAGE (ACRE- FEET)		72,098	48,884	43,136	2,627
THE MAXIMUM INUNDATED AREA IS(ACRES)		18,709	11,899	11,995	1,296



Table 4 - 6 FLO-2D Model Result Summary for 100-year Flood Event

SUB-DOMAINS:				
	Middle North	Middle South	Middle East	South
INFLOW:				
INFLOW HYDROGRAPH(ACRE-FEET)	87,493	71,329	64,210	4,766
WATER LOST TO INFILTRATION & INTERCEPTION(ACRE-FEET)	20,402	16,911	23,687	3,562
FLOODPLAIN STORAGE (ACRE-FEET)	17,637	14,684	21,436	1,203
FLOODPLAIN OUTFLOW HYDROGRAPH (ACRE- FEET)	49,454	39,733	19,073	0
TOTAL VOLUME OF OUTFLOW AND STORAGE (ACRE- FEET)	87,493	71,329	64,197	4,765
THE MAXIMUM INUNDATED AREA IS(ACRES)	19,293	13,832	14,081	2,188



Table 4 - 7 FLO-2D Model Result Summary for 500-year Flood Event

SUB-DOMAINS:		Middle North	Middle South	Middle East	South
INFLOW:					
INFLOW HYDROGRAPH(ACRE-FEET)		122,587	97,872	98,653	14,878
OUTFLOW:					
WATER LOST TO INFILTRATION & INTERCEPTION(ACRE-FEET)		23,675	22,799	29,884	10,034
FLOODPLAIN STORAGE (ACRE-FEET)		23,572	21,652	30,335	4,844
FLOODPLAIN OUTFLOW HYDROGRAPH (ACRE- FEET)		75,340	53,422	38,419	0
TOTAL VOLUME OF OUTFLOW AND STORAGE (ACRE-FEET)		122,587	97,872	98,639	14,878
THE MAXIMUM INUNDATED AREA IS(ACRES)		75,340	17,279	16,551	5,731



4.5 Determination of Floodplain Boundaries

FLO-2D model results were post-processed by the automated mapping tools of FLO-2D Mapper. FLO-2D Mapper tool can interpolate the flow depth data and generate the contour shape files for further processing. ArcGIS tool or the DFIRM tool, a separate tool from FLO-2D Company, can be used to generate the final electronic map.

Detailed maps showing flood hazard boundaries and flood depths are provided in Appendix D. The flood insurance risk zone type was determined according to the Appendix E of FEMA's Guidelines and Specifications for Flood Hazard Mapping Partners. The flood insurance risk zones for shallow flooding are described as (FEMA, 2002):

Zone A – “is the flood insurance risk zone that corresponds to the 1-percent-annual-chance floodplains that are determined by approximate-study methods.”

Zone AO – “is the flood insurance risk zone that corresponds to the areas of 1-percent-annual-chance shallow flooding (usually sheet flow on sloping terrain) where average depths are between 1.0 and 3.0 feet.”

Zone AH – “is the flood insurance risk zone that corresponds to the areas of 1-percent-annual-chance shallow flooding (usually areas of ponding) where average depths are between 1.0 and 3.0 feet.”

Zone X – “is the flood insurance risk zone that corresponds to areas outside the 0.2-percent-annual chance floodplain, and includes the following areas within the 0.2-percent-annual-chance floodplain: Those areas of 1-percent-annual-chance flooding where average depths are less than 1.0 foot; Those areas of 1-percent-annual-chance flooding where the contributing drainage area is less than 1.0 square mile, and the areas protected from the 1-percent-annual-chance flood of the main flooding source by levees.”



5 CONCLUSION AND LIMITATION

This report has documented the data, methodology and results for hydrologic and hydraulic analysis of the Northern Puna area. HEC-HMS model was used for hydrologic analysis and FLO-2D model was used for hydraulic analysis. The lumped HEC-HMS model requires knowledge of the flow direction in advance. HEC-HMS model does not automatically consider the flow diversion induced by topographic features. Flow diversion curves are generated by FLO-2D model when necessary for HEC-HMS to simulate the flow diversion. In the Puna study area, stream channels are not well developed, and the two dimensional FLO-2D model provides a better estimate of flow distribution in the watershed. Generally FLO-2D, as also a hydrology model, works well in the Puna study area, where the overland flow is prevalent. However, since FLO-2D hydrology model is not an accepted hydrology model by FEMA, the FLO-2D hydrology model is only presented for the comparison purpose (Appendix A).

The HEC-HMS model results were compared with the FLO-2D model results. The HEC-HMS results match well with the FLO-2D results. The differences between the two models at the major junctions are within 15%. Based on this comparison, HEC-HMS model results provide good estimations for the four storm events. The hydrologic results of HEC-HMS model are sufficiently accurate to use as input to the FLO-2D model in hydraulic analysis.

FLO-2D is listed on the FEMA's list of approved hydraulic models for riverine and unconfined flood studies. The project area mainly consists of recent lava flow and currently there are no well-defined stream channel due to the slow development of soil mantle and high permeability of the soil. Shallow flooding is dominated in this area. Historically surface sheet flow flooding ensues throughout the project area when large storm events occur.

The hydraulic calibration to the November 1 to 2, 2000 flood event proved that the FLO-2D model replicated historical flood closely. The hydraulic analysis found that the unconfined overland flooding is common at Puna area. Results of the FLO-2D model have demonstrated that model has performed consistently and reasonably.

There are still some limitations for this flood study:

LiDAR data from Airborne 1 USA were used to provide the FLO-2D terrain information. The LiDAR data used in this study meets the minimum standards to pass the quantitative assessment (vertical accuracy) and is marginally acceptable for detailed qualitative assessment. There are some errors and anomalies in the LiDAR data, which is common and typical for this type of geographic data in the dense vegetated areas like Puna. The FLO-2D model interpolated the LiDAR data by filter criteria and assigned an average topographic data for each grid size. This was done to alleviate the influence of the original data errors. In general, FLO-2D results are expected to be reasonable and reliable.

The hydraulic analysis assumed no sedimentation and debris blockages of the bridge openings. Water loss due to cavities and lava tubes were not considered in this study. This



study reflects flooding potentials based on conditions existing at the northern Puna area at the time of completion of this study. Maps and flood elevations should be amended periodically to reflect future changes.



REFERENCES

- Barnes, H. H. 1967. *Roughness characteristics of natural channels*. Washington, DC: US Government Printing Office.
- Chow, V. T. 1959. *Open Channel Hydraulics*. New York: McGraw-Hill Inc.
- City of Boulder Public Works Department, 2012, *Upper Goose Creek and Twomile Canyon Creek Flood Mapping Study Update*, 394p, Colorado.
- County of Hawai'i, Department of Planning. 1995. *Puna Community Development Plan*. Prepared by Community Management Associates, Inc.
- County of Hawai'i, Department of Planning. 2005. *Puna Regional Circulation Plan, Final report*. Prepared by Townscape, Inc.
- County of Hawai'i, Department of Public Works. 1974. *Mountain View Drainage Study and Master Plan*. Prepared by Austin, Smith & Associates, Inc.
- County of Hawai'i, Department of Public Works. 1976. *Mountain View Drainage Improvements, Environmental Impact Statement*. Hilo, Hawaii.
- County of Hawai'i, Department of Public Works. 1970. *Storm Drainage Standard*. Hilo, Hawaii.
- Dewberry, 2010. *QAQC Report, Oceanit: Puna, Hawaii*. Fairfax, VA.
- Druecher, Michael and Fan, Pow-foong. 1976. *Hydrology and Chemistry of Ground Water in Puna, Hawai'i Ground Water* 14(5): 328-338.
- Facts about Puna Hawai'i. 2012. <https://www.punaguide.com/puna-hawaii.html>.
- Federal Emergency Management Agency. 2004. *Flood Insurance Study, Hawaii County, Hawaii*. Washington, DC: US Government Printing Office.
- Federal Emergency Management Agency. 2003. *Guidelines and Specifications for Flood Hazard Mapping Partners*. Washington, DC: US Government Printing Office.
- Federal Emergency Management Agency. 2007. *Requirements of 44 CFR Section 65.10: Mapping of Areas Protected by Levee Systems*.
- Federal Emergency Management Agency. 2011. *Analysis and Mapping Procedures for Non-Accredited Levees*.
- FLO-2D Software, Inc. 2006. *FLO-2D user's manual, Version 2006.01*.



- FLO-2D Software, Inc. 2009. *FLO-2D Reference manual*, 2009.
- Hawaiian Acres Community Association. 2011. *The History, Biology, Geology and Current Living Conditions of Hawaiian Acres*. <http://www.hawaiianacres.org/history.shtml>
- Interagency Advisory Committee on Water Data. 1982. *Guidelines for determining flood flow frequency (Bulletin #17B of the Hydrology Subcommittee)*. Reston, VA.
- James, W.P., J. Warinner, and M. Reedy. 1992. *Application of the Green-Ampt Infiltration Equation to Watershed Modeling*. *Water Resources Bulletin* 28(3): 623-635.
- Juvik, Sonia P. and Juvik, James O.. 1983. *Atlas of Hawaii, third edition*. Honolulu: University of Hawai'i Press
- Lau, L. S., & Mink, J. F. 2006. *Hydrology of the Hawaiian Islands*. Honolulu: University of Hawai'i Press.
- Lee, Rhodes Diane. 2001. *A cultural history of three traditional Hawai'i sites on the west coast of Hawai'i island. Overview of Hawaii History*.
(<http://www.donch.com/LULH/culturehist6.htm>)
- Loucks, Eric. 2009. *FEMA Levee Analysis Guidelines* PowerPoint slides. National Oceanic and Atmospheric Administration. 2011. *Precipitation Frequency Data Server*. Available from <http://hdsc.nws.noaa.gov/hdsc/pfds/>
- MacDonald, G. A., Abbott, A. T., and Peterson, F. L. 1970. *Volcanoes in the sea: The geology of Hawaii*. Honolulu: University of Hawai'i Press.
- Natural Resources Conservation Service. 1986. *Urban Hydrology for small watersheds (Technical Release 55)*. Washington, DC: US Government Printing Office.
- Natural Resources Conservation Service. 2006. *Physical Soil Properties, Island of Hawaii*. Washington, DC: US Government Printing Office.
- National Weather Service Forecast Office, Honolulu, HI. *Hawaii Archived Hydronet Data*. Available from <http://www.prh.noaa.gov/hnl/hydro/hydronet/hydronet-data.php>
- National Oceanic and Atmospheric Administration, *Precipitation Frequency Data Server. Atlas 14 Point Precipitation Frequency Estimates*. Available from <http://hdsc.nws.noaa.gov/hdsc/pfds/>
- Oki, Delwyn S. 2003. *Surface Water in Hawai'i*. U.S. Geological Survey.
- Perica, S., Martin, D. B. Lin, Parzybok, T., Riley, D., Yekta, Hiner, M. L., Chen, L.-C. Brewer, D., Yan, F., Maitaria, K., Trypaluk, C., Bonnin, G.M.. 2009). *Precipitation-Frequency Atlas of the United States*. NOAA Atlas 14, Volume 4, Version 2, NOAA, National



Weather Service, Silver Spring, Maryland, 2009 Extracted: Tue April 18, 2011. Available from http://hdsc.nws.noaa.gov/hdsc/pfds/hi/hi_pfds.html

Puna Weather. 2012. <http://www.punaguide.com/Puna-weather.html>

Sato, H.H., Ikeda, W., Paeth, R., Smythe, R. and Takehiro, Jr. M. 1973. *Soil Survey of the Island of Hawaii, State of Hawaii*. USDA, Soil Conservation Service, Washington, DC

Stearns, H.T., and Macdonald, G.A. 1946. *Geology and Ground-water Resources of the Island of Hawai'i: Hawai'i (Terr.)* Division of Hydrography Bulletin 9, 363 p.; 2 folded maps in pocket (scale 1:125,000) [includes plates].

Sonia, P. Juvik, and James, O. Juvik. 1983. *Atlas of Hawai'i, third edition*. Honolulu: University of Hawai'i Press.

Tetra Tech, Inc. 2002. *Development of the Middle Rio Grande FLO-2D Flood Routing Model Cochiti Dam to Elephant Butte Reservoir*. New Mexico.

University of Hawai'i at Hilo. 2003. *Natural Hazards Big Island-Flood Hazards Gallery*. http://hilo.hawaii.edu/~nat_haz/floods/gallery.php.

U.S. Army Corps of Engineers, Honolulu District. 1990. *Alenaio Stream Flood Control Project, Hilo, Hawai'i, General Design Memorandum and Environmental Assessment Study*.

U.S. Army Corps of Engineers, Honolulu District. 2006. *Waiakea Stream Flood Damage Reduction Feasibility Study, Hilo, Hawai'i*.

U.S. Army Corps of Engineers. 1997. *Technical Engineering and Design Guide*, No. 19.

U.S. Geological Survey, Water Resources Investigations Report 02-4117. 2002. *Streamflow and Erosion Response to Prolonged Intense Rainfall of November 1-2, 2000, Island of Hawaii, Hawaii*. By Richard A. Fontaine and Barry R. Hill.

U.S. Geological Survey, Report Series 2007-1264. 2007. *Lava Flow Hazard Assessment, as of August 2007, for Kilauea East Rift Zone Eruptions, Hawaii Island*. By Jim Kauahikaua.

Wright, Thomas L. and Fiske, Richard S. 1971. *Origin of the Differentiate and Hybrid Lavas of Kilauea Volcano, Hawai'i*. 12(1). 1-65.

Appendix A

FLO-2D HYDROLOGY MODEL DEVELOPMENT



APPENDIX A

A. FLO-2D Hydrology Model Development

A.1 FLO-2D Model Overview

FLO-2D is a two-dimensional flood routing model that can simulate unconfined overland flow, channel flow, floodwave attenuation, floodplain inundation, spatially variable water depth and infiltration. FLO-2D is based on a volume conservation principle that distributes a flood hydrograph over a system of grid elements developed from a Digital Terrain Model (DTM). The equation of motion (i.e., full dynamic wave momentum equation) is solved by computing the average flow velocity across each grid element boundary. The program calculates values in eight potential flow directions—the four compass directions (north, east, south, and west) and the four diagonal directions (northeast, southeast, southwest, and northwest) (Tetra Tech, Inc. 2002). According to *FLO-2D User Manual* (2006), the FLO-2D model has the advantage of representing the grid system's spatial variability over complex topography and roughness.

FLO-2D (Version 2009) is a FEMA-approved hydraulics model and can be used for both hydrologic and hydraulic analyses. Rainfall and runoff can be simulated in the FLO-2D model to generate hydrographs for downstream watercourses. The storm rainfall is discretized as a cumulative percent of the total precipitation and can be assigned on the model domain using a temporal distribution.

In the Puna Flood Study, FLO-2D (Version 2009) was employed to perform the hydrologic analyses for the purpose of comparison with the HEC-HMS model results. As an integrated flood routing model, FLO-2D couples hydraulic simulation with hydrologic simulation. The FLO-2D model for this study was set up and executed for both hydrologic simulation and hydraulic simulations. The FLO-2D computations were carried out over the whole watershed; therefore calculating the time of concentration was unnecessary.

A.1.1 Topographic Database

Terrain data must be provided in a DTM file to start a flood simulation in FLO-2D. Oceanit obtained light detection and ranging (LiDAR) data from the County, which has a separate contract with Airborne 1 to collect the data. The LiDAR data were collected from 2007 through 2008. The product is a mass point dataset with an average point spacing of 8 feet. Oceanit formed the DTM data for the Puna Study Area with a re-sampling resolution of 16 feet by 16 feet. This resolution gives one elevation point within an area of 256 square feet (ft²). The re-sampled data from Airborne 1 was used to build the FLO-2D models using a 128-foot x 128-foot grid cell size. Each grid element contained an average of 64 elevation points from which the grid elevations were determined.

At the areas with significant structures, such as the South Kūlani Flood Diversion Structure the major bridges, and culverts, the ground survey data were used to better define the elevations of these structures. All elevation data utilized were based on the North American



Horizontal Datum of 1983 (NAD-1983-HARN-StatePlane-Hawaii-1-FIPS-5101-Feet). The vertical datum was based on the tidal datum.

The FLO-2D software package includes a grid developer system (GDS), which prepares the basic input files and overlays the grid system on a DTM set of points. The main purpose of the GDS is to filter DTM points, interpolate the DTM data, and assign required parameters to grid elements. In general, the GDS prepares input files for running the FLO-2D model.

A.1.2 Estimation of Manning's "n" Values for Overland Flow

In the formulation of the kinematic wave approximation for overland flow, the Manning's "n" value or overland flow roughness coefficient plays an important role. Higher the roughness of the surface, the flow is retarded more and hence the slower the overland velocity. Suggested typical value of "n" for overland flow on the surface are in the range of 0.2 to 0.35 and does not represent realistic values of "n" that might be used in channel flow calculations. The overland flow of the FLO-2D model is routed in eight possible flow directions for each grid element; each cell is treated as an octagon rather than a square. Typical Manning's "n" values for overland flow can be found in Table 2 of the FLO-2D user manual.

The Manning's "n" values of the final model were assigned into three separate categories: the overland or sheet flow area, the shallow concentrated flow area, and the stream channel. The final selected "n" values for the overland flow area in the Puna study area were 0.10 to 0.15 (FLO-2D Reference Manual, 2009), and a typical value of 0.125 was used in most overland flow areas. The overland flow path is primarily a function of the topography. For those areas with deeper water, lower "n" values were assigned to the grid cells; whereas the higher n values used were assigned to grid cells with lower water depth. For residential areas, the "n" values used were 0.065 to 0.10 according to the different surface conditions such as roads, and grass. The "n" values for stream channels delineated by the FLO-2D model ranged from 0.045 to 0.065.

A.1.3 Estimation of Infiltration Rates

Infiltration is the process by which water seeps into the ground through the surface. The infiltration rate depends on soil texture and compaction, initial soil water content, vegetative cover, and the rate of precipitation. The soil types in the Puna study area are shown in Section 3.4 Basin Loss. Spatially variable infiltration rates were graphically assigned in the GDS program. Infiltration in FLO-2D is simulated using the Green-Ampt infiltration method that assumes a ponding condition and a uniformly advancing wetting front, which is subjected to a soil suction head. The five parameters of the Green-Ampt infiltration method include hydraulic conductivity, capillarity suction, soil moisture deficit, rainfall abstraction, and the impervious area for floodplain elements. Only hydraulic conductivity is relevant for channel elements. The Green-Ampt infiltration parameters used for this study are the same as those used by the HEC-HMS model.



A.1.4 FLO-2D Model Sub-domains

The total study area of 180,480 acres (282 mi²) was divided into five smaller areas or sub-domains for modeling with a 128-foot by 128-foot grid cell size. The selected grid cell size provides sufficient resolution to represent topographic variations in the study area. The five sub-domains (Shown in Figure A-1) were labeled North, South, Middle North, Middle South and Middle East. The sub-domains were delineated based on the available LiDAR topographic data. The North and South sub-domains are independent of the other sub-domains. The Middle North sub-domain receives inflow from the Middle South sub-domain, and the Middle East sub-domain receives inflow from both the Middle North and Middle South sub-domains.

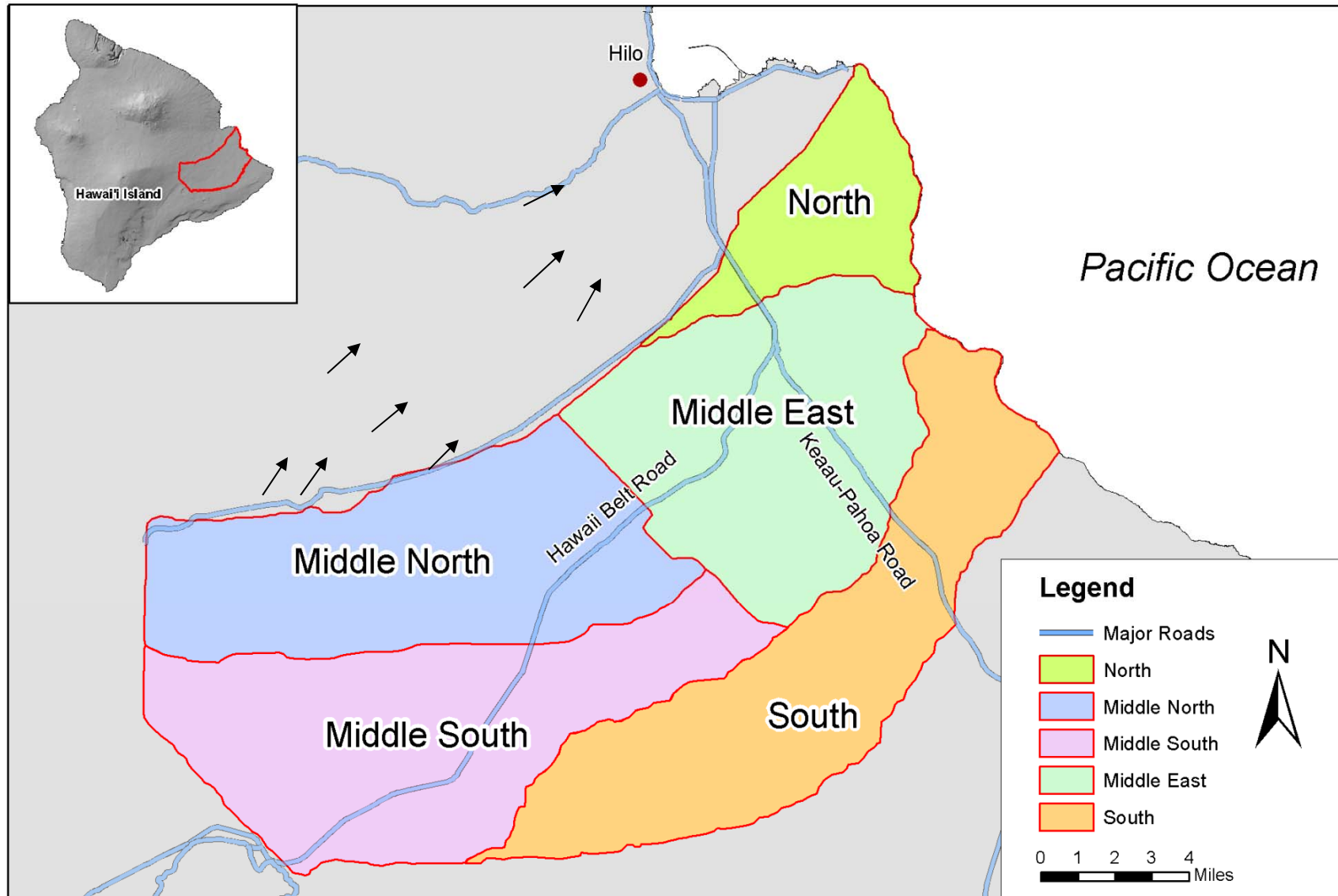


Figure A - 1 FLO-2D Model Subdomains



A.1.5 Meteorological Events

The Puna study area covers a very large area and the intensity and distribution of rainfall vary greatly from sub-watershed to sub-watershed. The study area was divided into 39 sub-watersheds, as shown in Figure 3-1 in Section 3. As a grid system model, FLO-2D allows to apply the rainfall in each grid. In this study, the rainfall amount was applied through the sub-watersheds in FLO-2D to have an easy comparison with the HEC-HMS model. The meteorological events used to simulate the rainfall represent varied return periods in a 24-hour duration. Precipitation frequency estimates from NOAA Atlas 14 (NOAA 2009) were used to determine the total cumulative rainfall produced by 10-, 50-, 100-, and 500-year frequency storms in the study area. Atlas 14 contains precipitation frequency estimates for the United States and U.S. affiliated territories (Perica, et al. 2009). The precipitation in the centroid of a particular sub-watershed was applied to the entire sub-watershed uniformly. The precipitation values used for the 10-, 50-, 100-, and 500-year return storm events in a 24-hour were plotted in Figures 3-6 through 3-10 in Section 3. The number in each sub-watershed is the rainfall value that was used. The rainfall for each model sub-domain was obtained by calculating the weighted average of the sub-watersheds in each model sub-domain. Table A-1 lists the calculated rainfall for the various storm return periods in each domain.

With the IDF for each sub-watershed available, hyetographs were generated from the HEC-HMS frequency storm method with an intensity position at 50%. Figure A-2 shows a typical 24-hour, 100-year accumulated hyetograph for the study area

Table A - 1 Rainfall for Each FLO-2D Model Sub-domain

Return Period	24-hour Rainfall (in)				
	North	Middle South	Middle North	Middle East	South
10-year	13.70	15.98	16.17	14.46	13.94
50-year	18.95	21.61	22.15	19.88	19.14
100-year	21.36	24.20	24.56	22.35	21.50
500-year	27.36	30.18	30.60	28.51	27.36



Rainfall Distribution

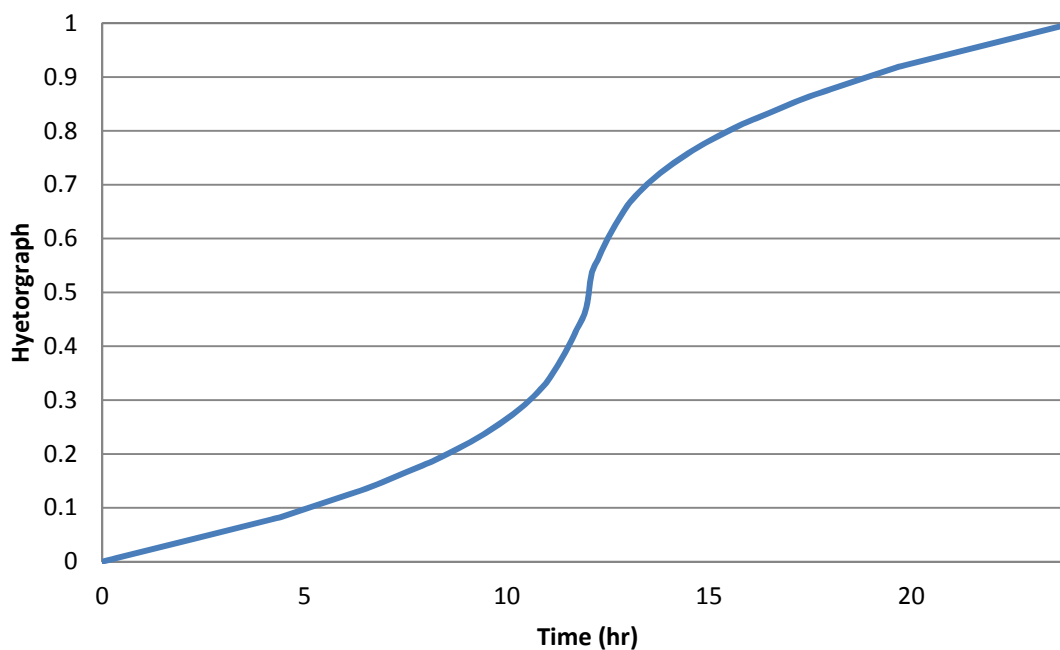


Figure A - 2. Typical 24-hour, 100-year Accumulated Rainfall Distribution.

A.1.6 FLO-2D Model Results

The hydrologic results of the FLO-2D model are presented in Table A-2. This table lists the results by storm return period and junction. The nine major junctions are identified in Figure ES-1 and represent key locations in the study area of converging floodwaters. These junctions were selected to compare the hydrologic results of the FLO-2D model with the peak discharges given by the HEC-HMS model (Table A-2).



Table A - 2. Puna Study Area FLO-2D Results.

Junctions	Description	Drainage Area (mi ²)	10-year (10% Annual Chance) cfs	50-year (2% Annual Chance) cfs	100-year (1% Annual Chance) cfs	500-year (0.2% Annual Chance) cfs
J2	Volcano Rd & Kahaualeale Rd	22.90	9,596	22,330	33,418	46,266
J3	Near Mauaana Rd	43.66	17,648	36,532	54,024	74,770
J4	Near ʻĀpele Rd	52.21	17,410	31,291	44,008	63,610
J5	South Kūlani Rd Bridge	78.00	20,684	39,041	51,602	75,217
J7	Keaʻau-Pāhoa Rd & Keaau Bypass Rd	109.63	14,734	31,463	40,507	59,910
J8	Volcano Rd & Huina Rd	23.25	6,017	13,046	16,191	24,023
J10	Railroad Ave. & Keaʻau Rd	16.10	1,248	3,684	5,640	11,935
JK1	Pulelehua Rd & Poola Rd	28.32	777	7,360	16,165	29,194
J16	Waimakao Pele Rd & Pahoehe Rd	10.14	171	1,080	2,608	8,581

Appendix B
FIELD SURVEY SOUTH KULANI BRIDGE DIVERSION STRUCTURE



APPENDIX B

Oceanit contracted the ParEn, Inc. dba Park Engineering to conduct a detail hydraulic diversion structure survey downstream the South Kūlani Bridge. ParEn, Inc. dba Park Engineering surveyed the structure during October, 2011. The survey started from the South Kūlani Bridge and cross-sections were measured in about 100 feet interval and additional cross-sections were taken when necessary. For each cross-section where a wall exists, two points on the top of the wall together with one point at the front of the wall and another point at the back of wall were taken. Figure B1 provides the survey points along the project site. The points of each cross-section is named by the structure suffix ("S1" represents Structure 1 and "S2" represents Structure 2) followed by the section number. Figure B2 shows the real structures and in some sections a slope in front of the wall is also depicted. Figure B3 through B11 provide the surveyed cross-sections comparing with the LiDAR data.

The surveyed data and the LiDAR data generally show similar flow confinement effects since the crest elevation of the rock wall is not higher than the landward ground elevation in most of the places. The surveyed cross-sections only show very few pronounced difference from the LiDAR data.

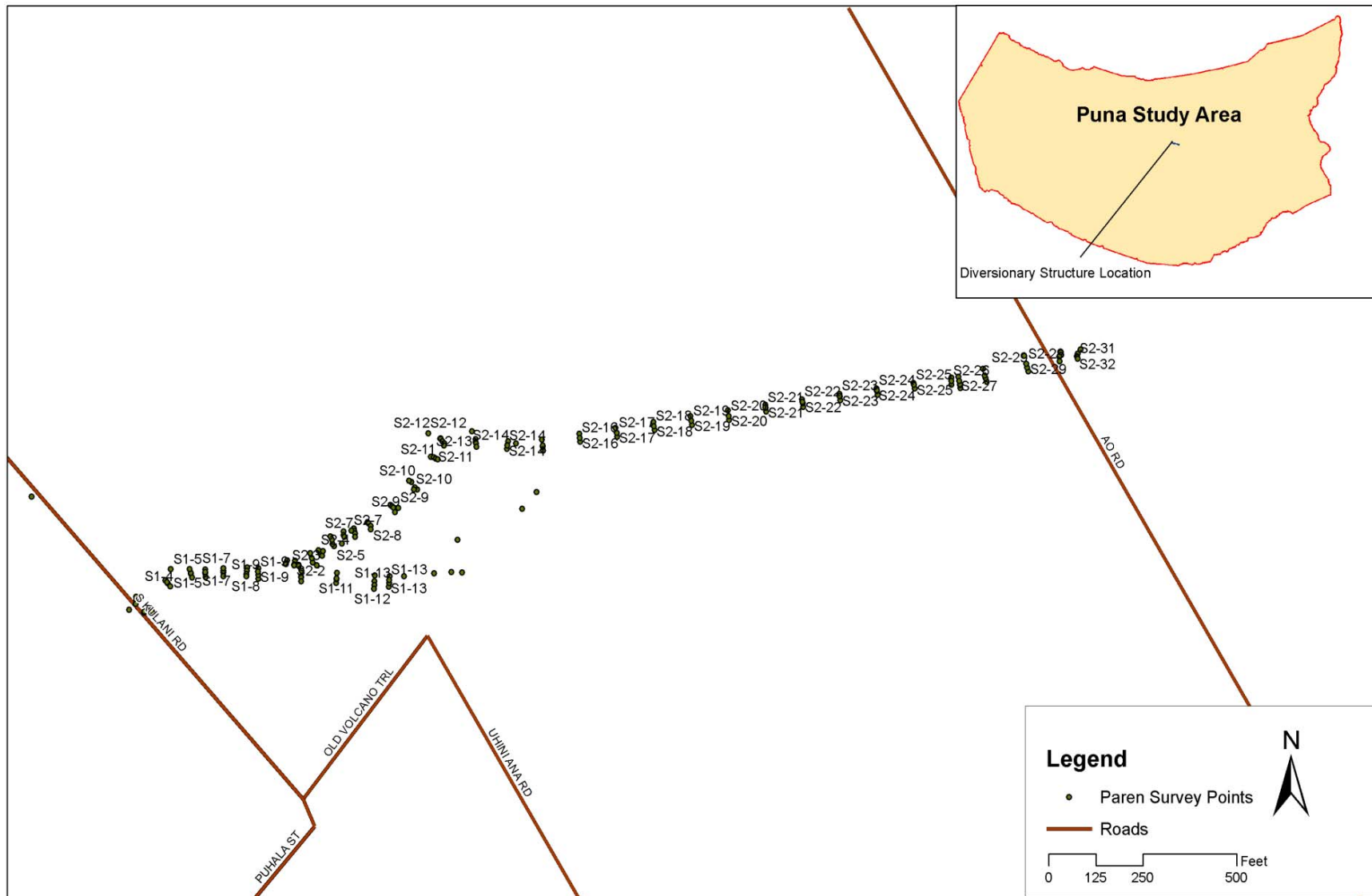


Figure B - 1 Hydraulic Structure Survey Points.

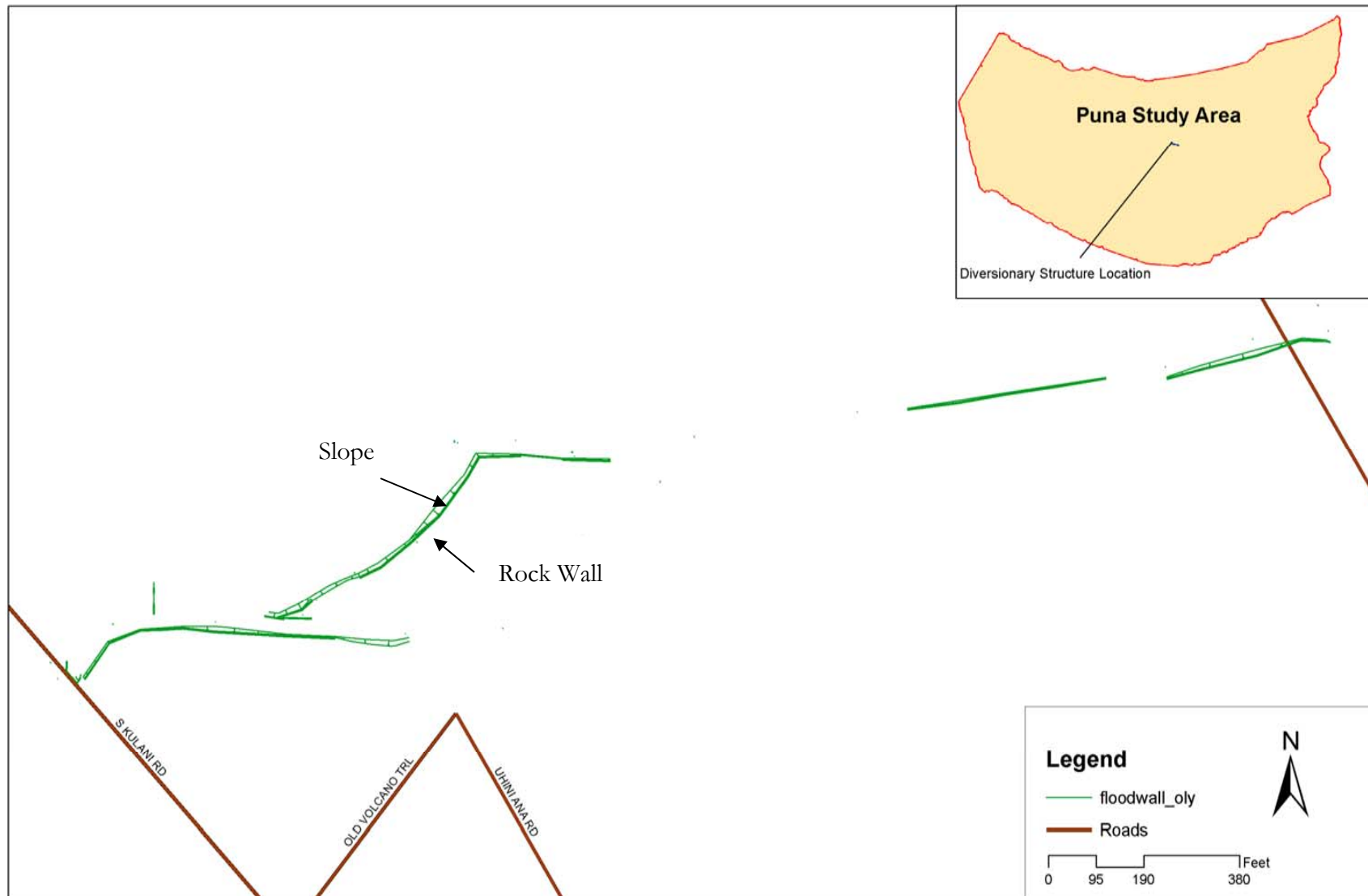


Figure B - 2 Hydraulic Diversion Structures.

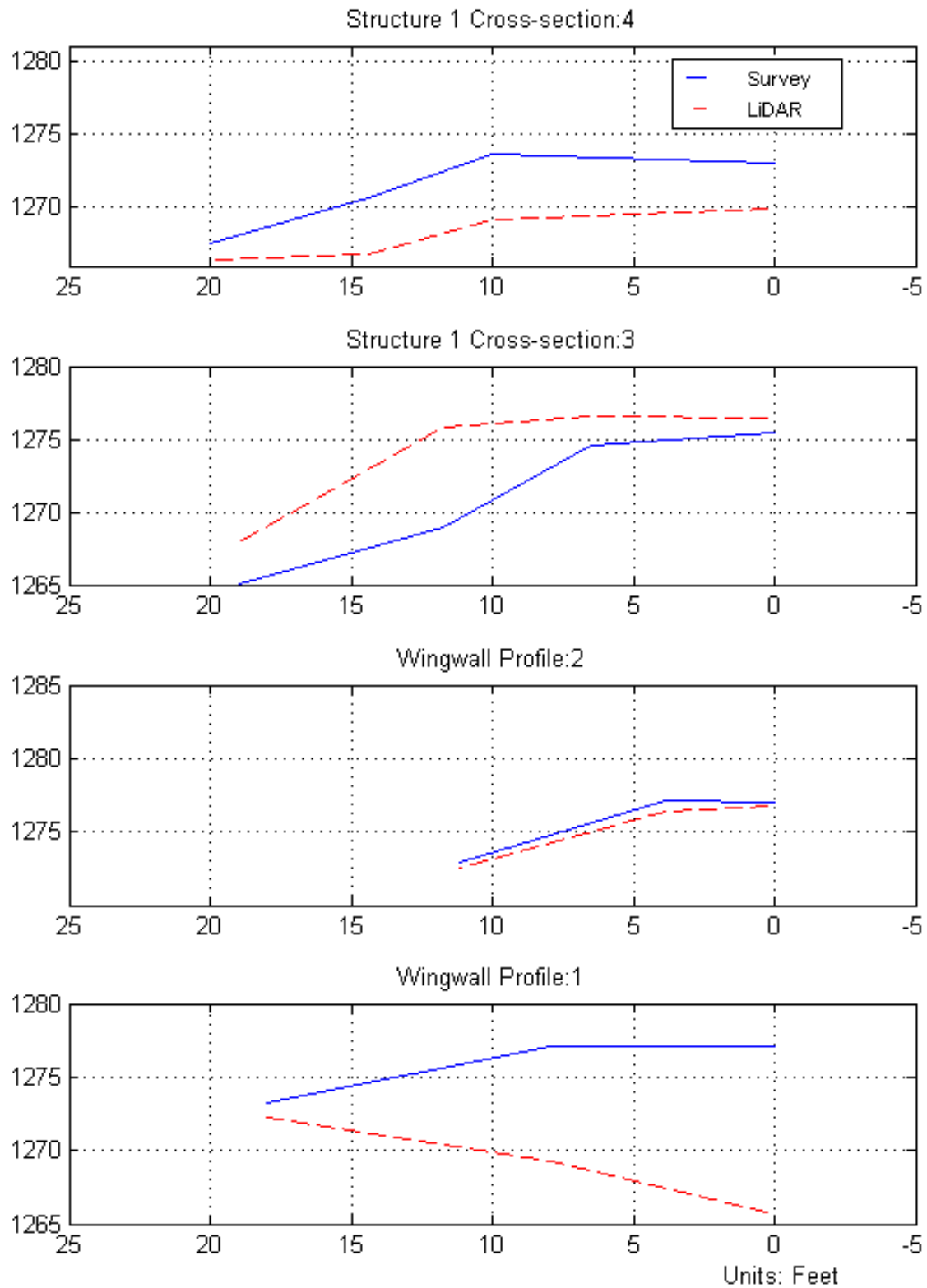


Figure B - 3. Surveyed Cross-sections.

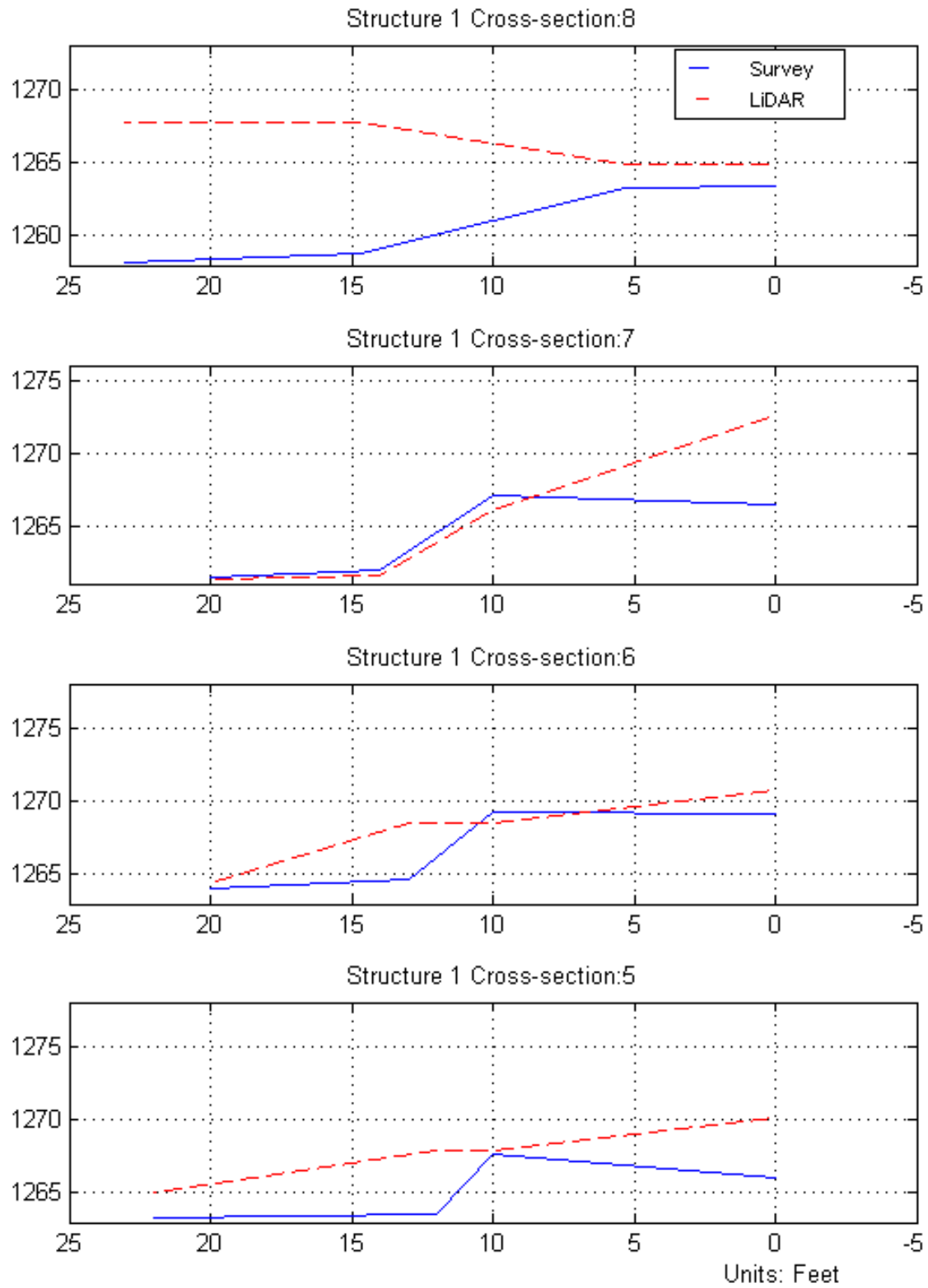


Figure B - 4. Surveyed Cross-sections (continued).

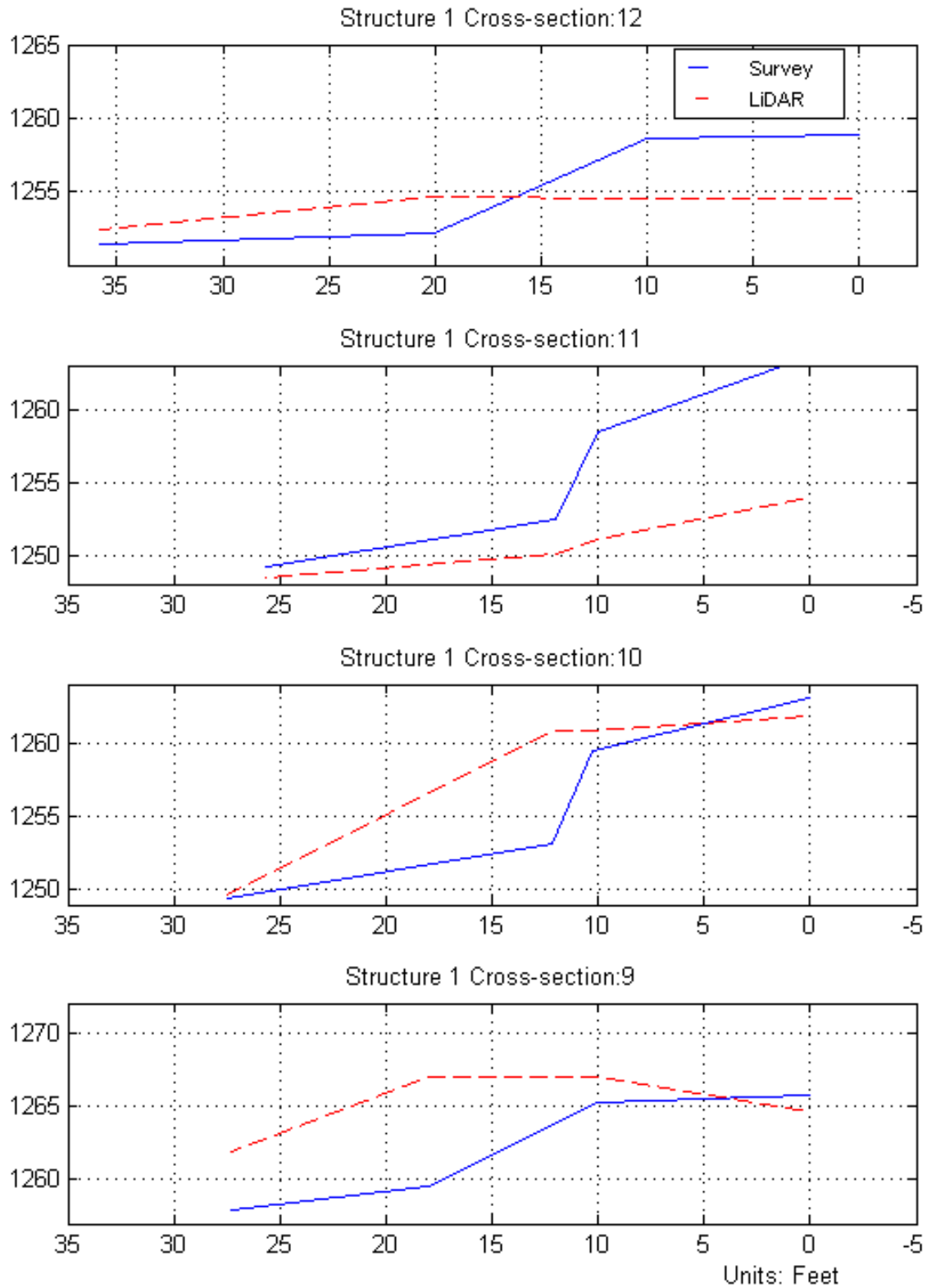


Figure B - 5.. Surveyed Cross-sections (continued).

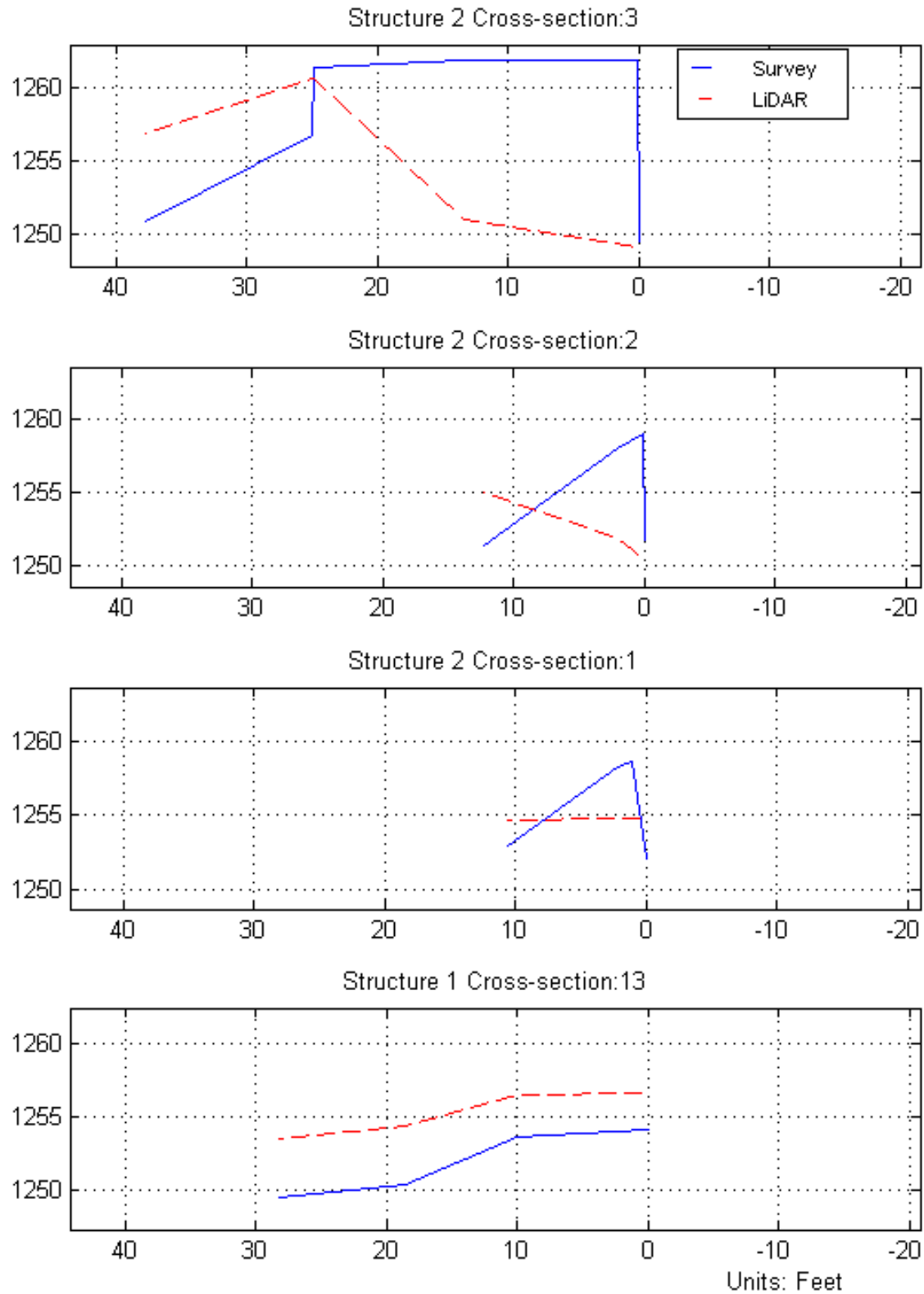


Figure B - 6. Surveyed Cross-sections (continued).

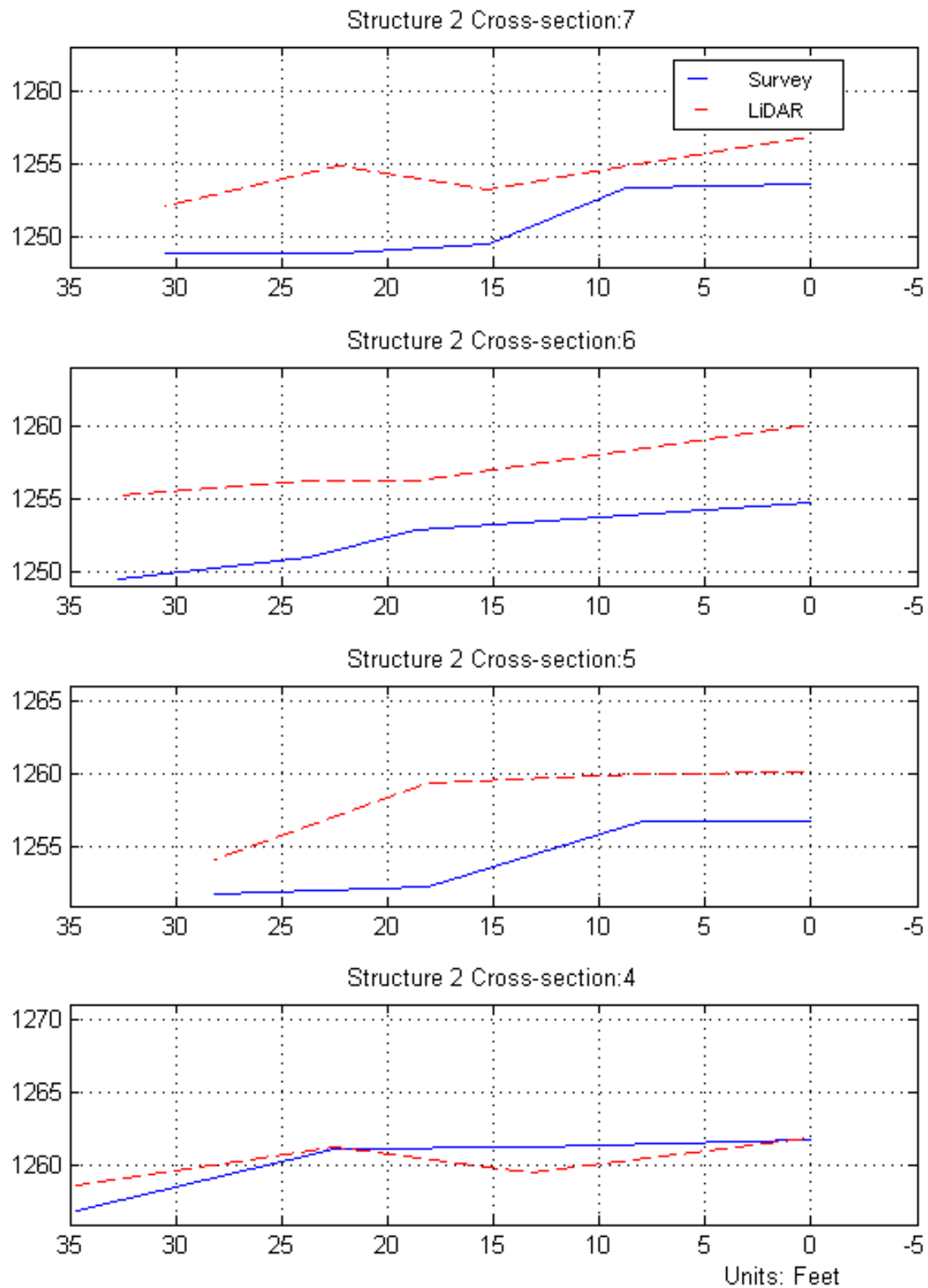


Figure B - 7. Surveyed Cross-sections (continued).

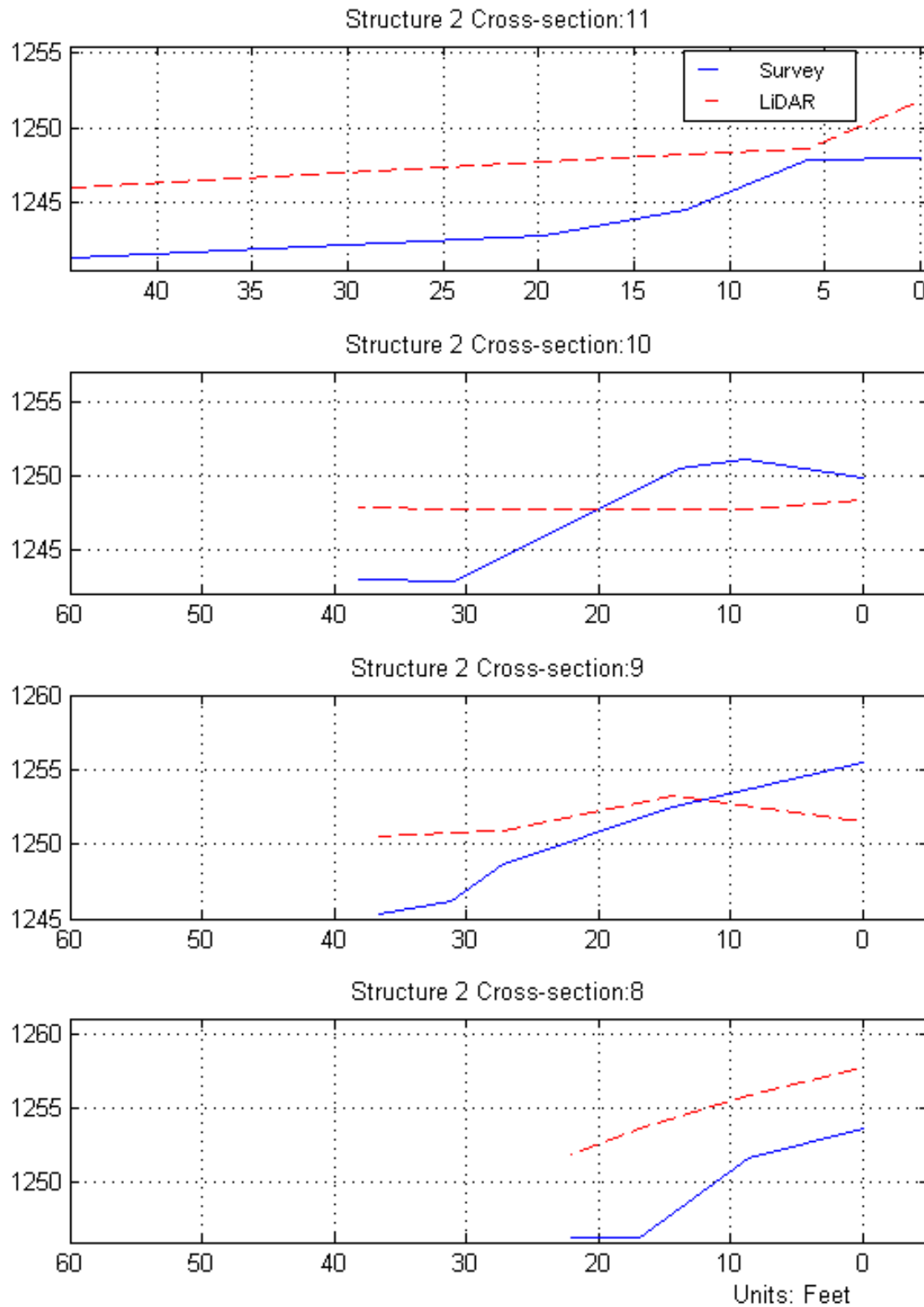


Figure B - 8. Surveyed Cross-sections (continued).

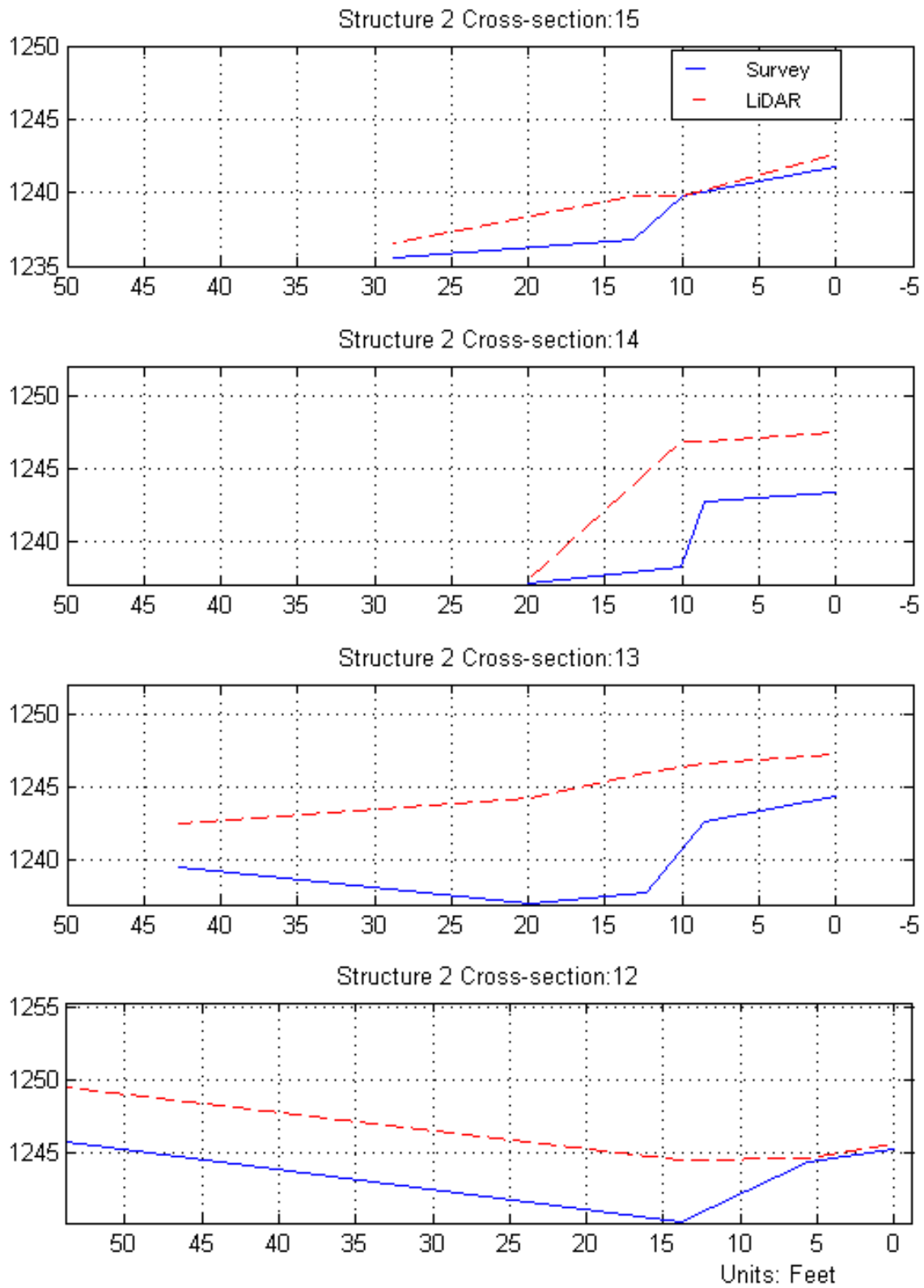


Figure B - 9. Surveyed Cross-sections (continued).

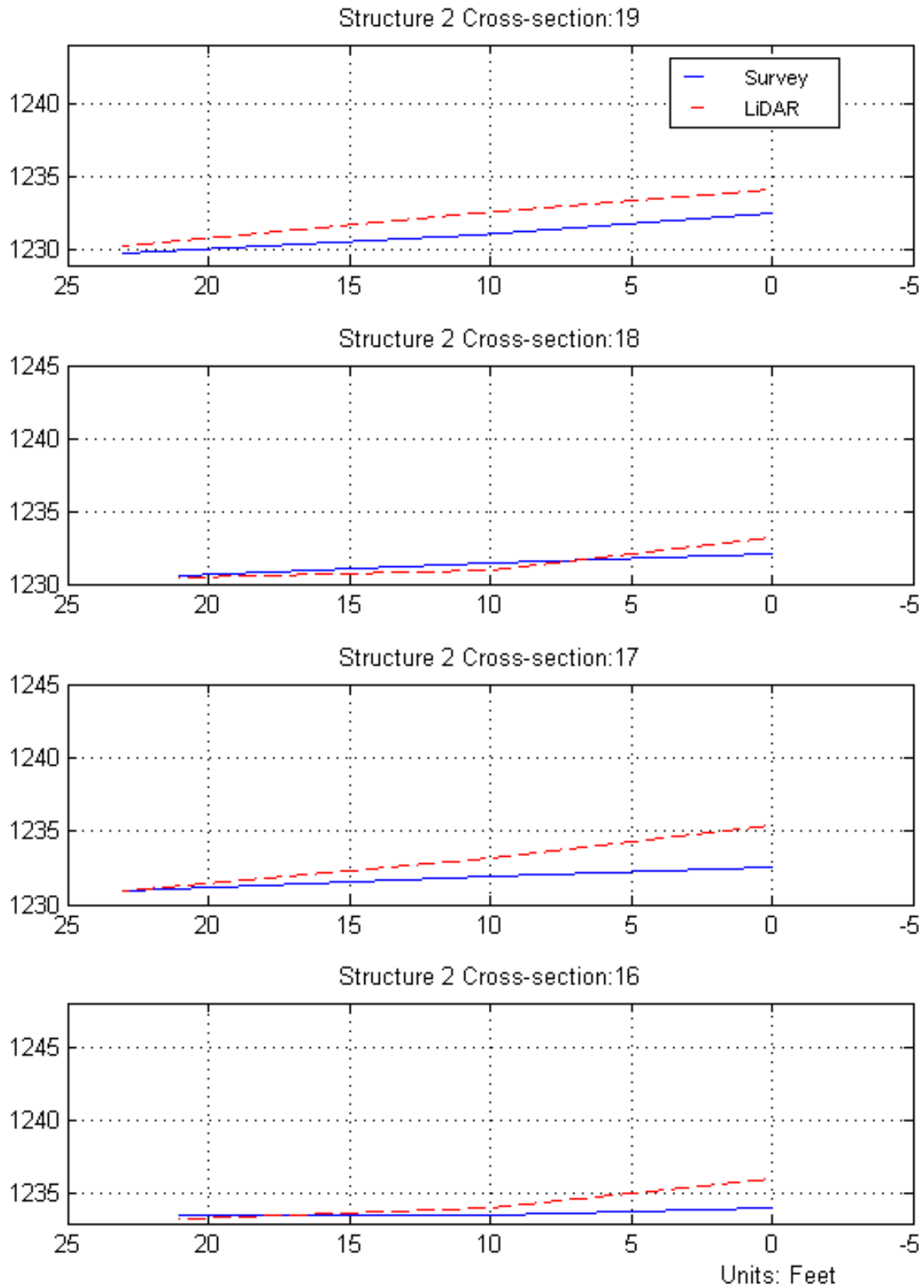


Figure B - 10. Surveyed Cross-sections (continued).

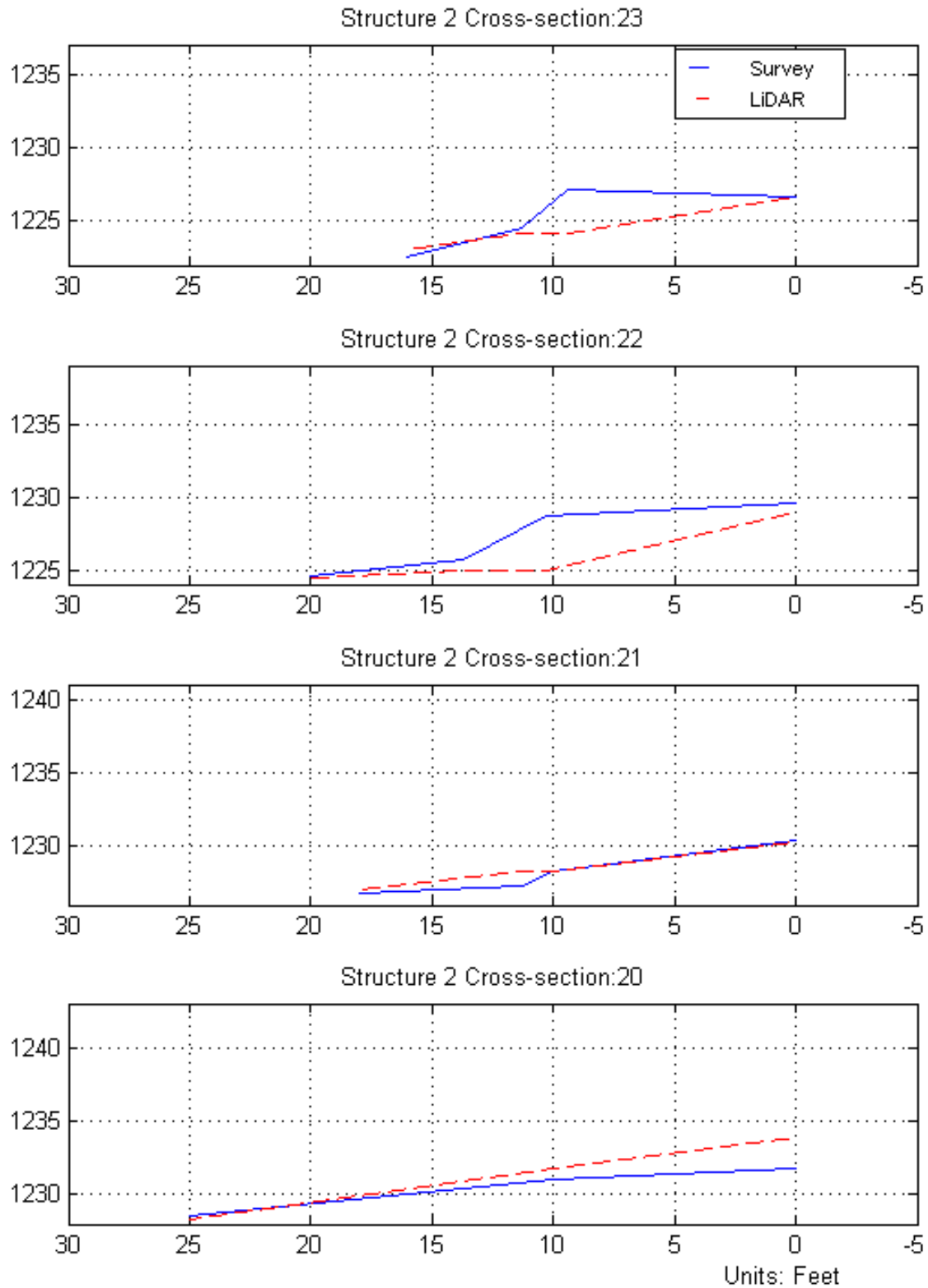


Figure B - 11. Surveyed Cross-sections (continued).

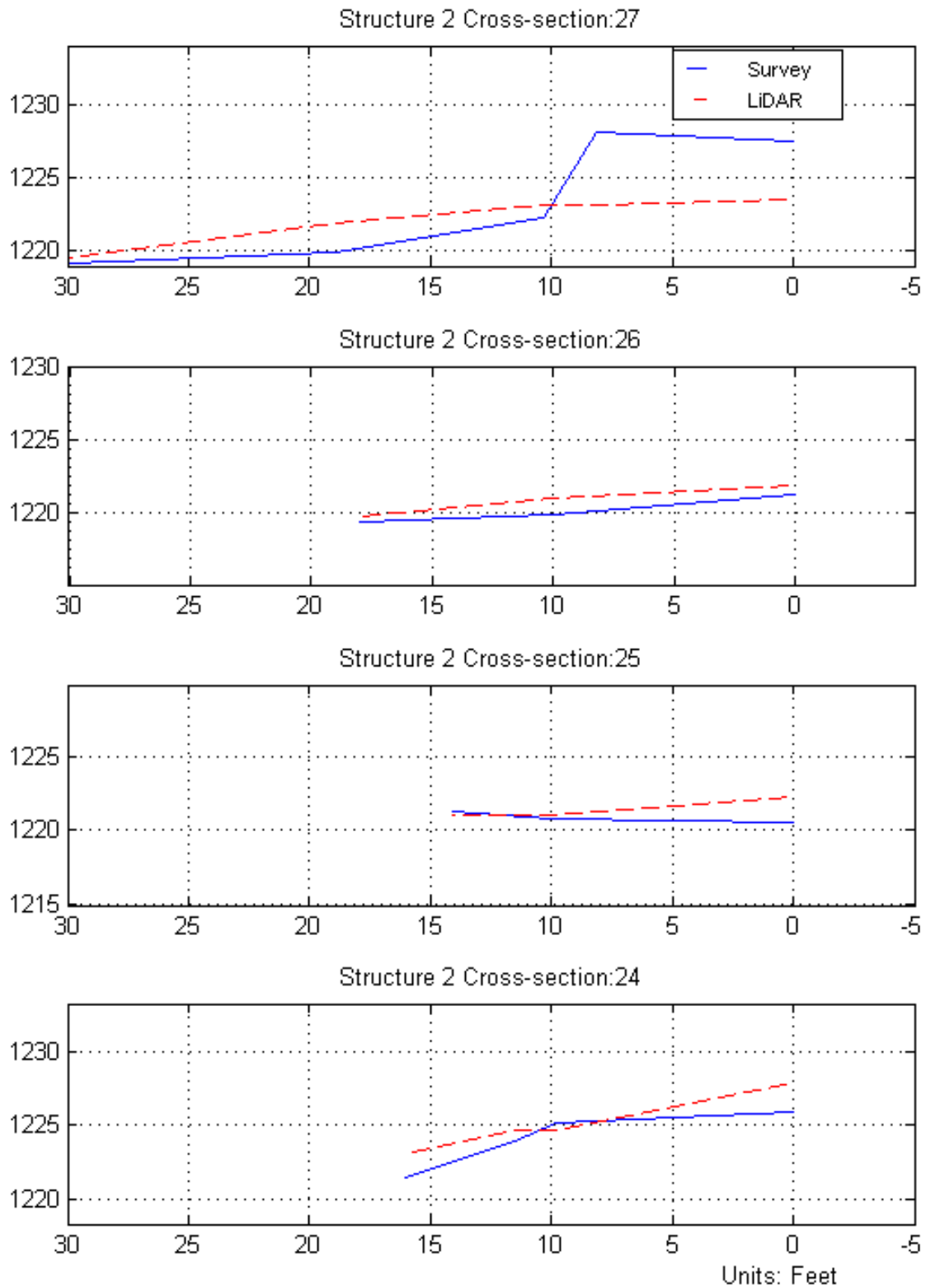


Figure B - 12. Surveyed Cross-sections (continued).

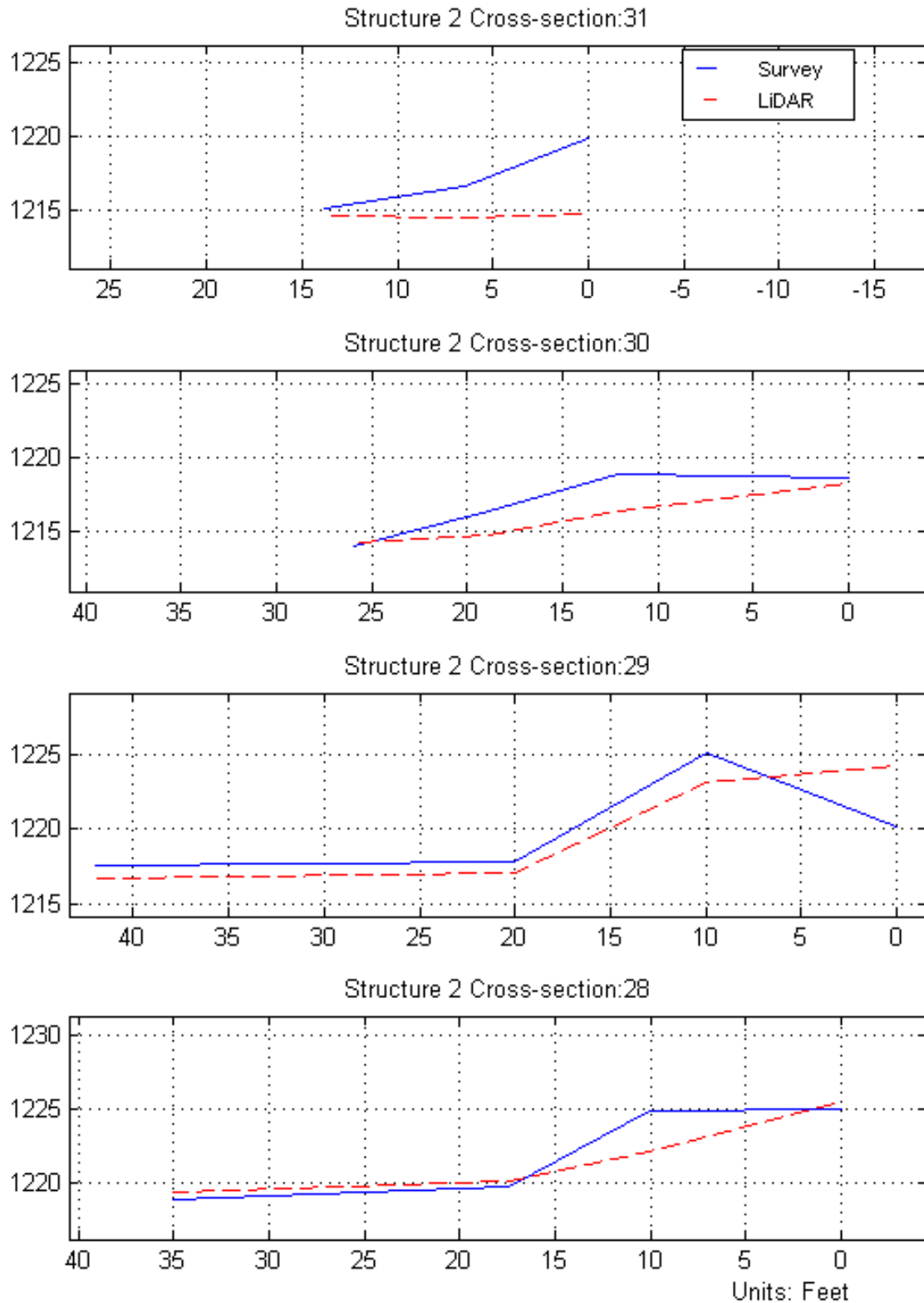


Figure B - 13. Surveyed Cross-sections (continued).

Appendix C

FIELD SURVEY ROADWAY CULVERTS & BRIDGE CROSSINGS



APPENDIX C

The field survey team from Oceanit surveyed the major hydraulic structures in the Puna area during June 14 to 15, 2011. The team applied the GPS instrument (ProHX by Trimble) to locate and record the critical points on the hydraulic structures. Generally four critical points on the bridge were geo-referenced using the GPS. Those four critical points are the locations of the top center of the bridge abutments. Geo-reference photos were taken at each location to record the details. A tape was then used to refer the other measurements to these geo-referenced points. The basic measurements included the deck width, the stream bed depth in the channel, the distance from the deck to the stream bank, the hydraulic width, and the pier size if applicable. The measurements were taken at both upstream side and downstream side of the bridges. For the culverts, GPS points were usually taken in the top center of the headwall. The culvert size and stream bed depth were measured by tape. Notes on the stream bed conditions, head wall, and wing wall were taken. Sketches were made if necessary. The GPS coordinates were corrected according to the Benchmark Coconut (Figure B1) near the intersection of Hawaii Belt Road and Old Volcano Road at Keaau Town.

The dimensions of the 12 hydraulic structures are listed as follows with photos if applicable (Notice the difference in horizontal and vertical scales). Rating curves achieved by the HEC-RAS modeling are plotted.



Figure C- 1. Benchmark for GPS Instrument Error Correction.



1) Keaau-Pahoa Road Culvert 1



Figure C- 2. Photo of the Keaau-Pahoa Road Culvert 1.

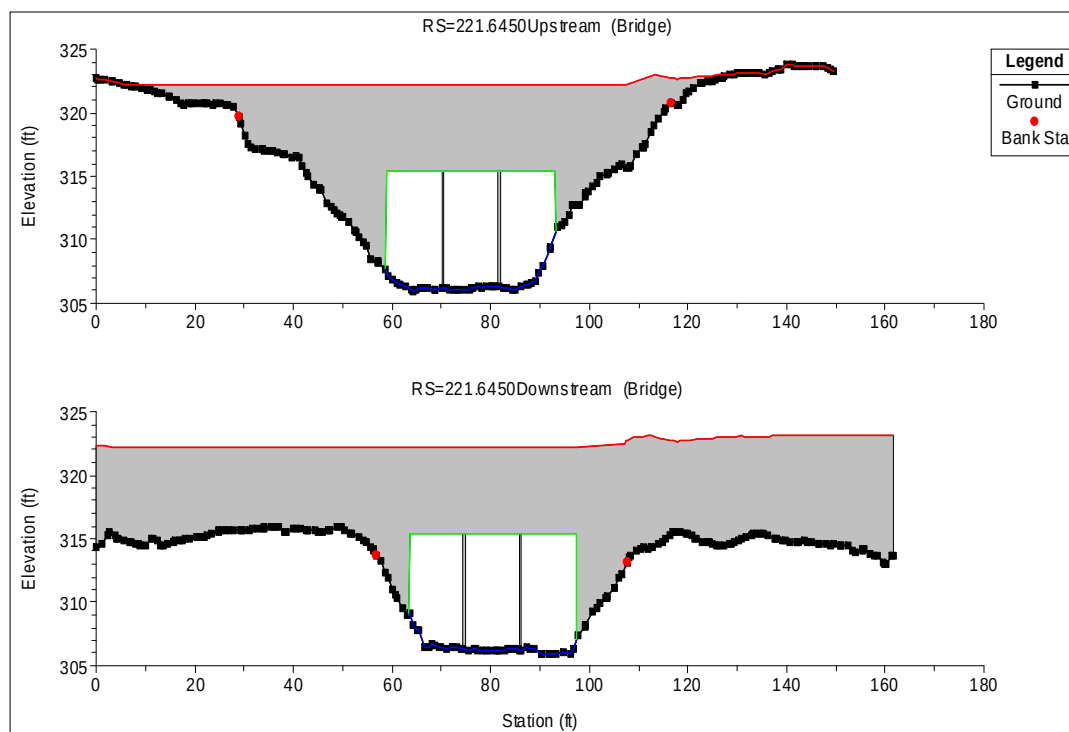


Figure C- 3. Cross-sections of the Keaau-Pahoa Road Culvert 1.

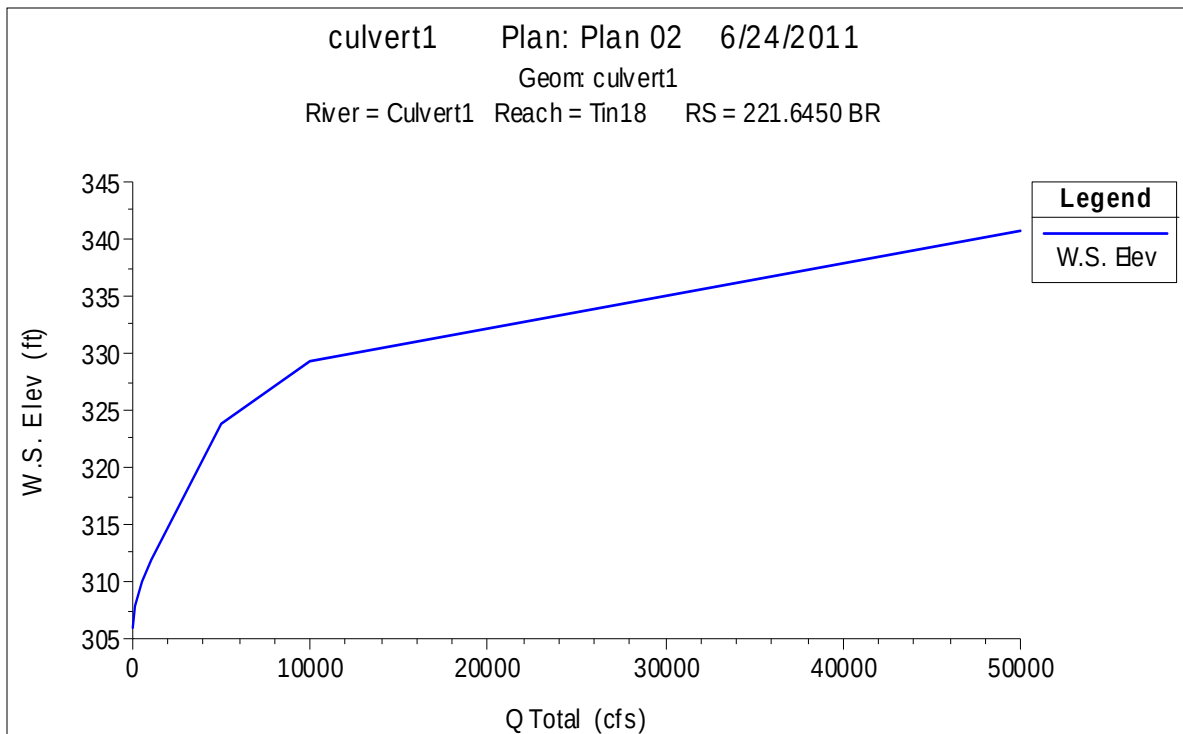


Figure C- 4. Rating Curve of the Keaau-Pahoa Road Culvert 1.

2) Keaau-Pahoa Road Culvert 2

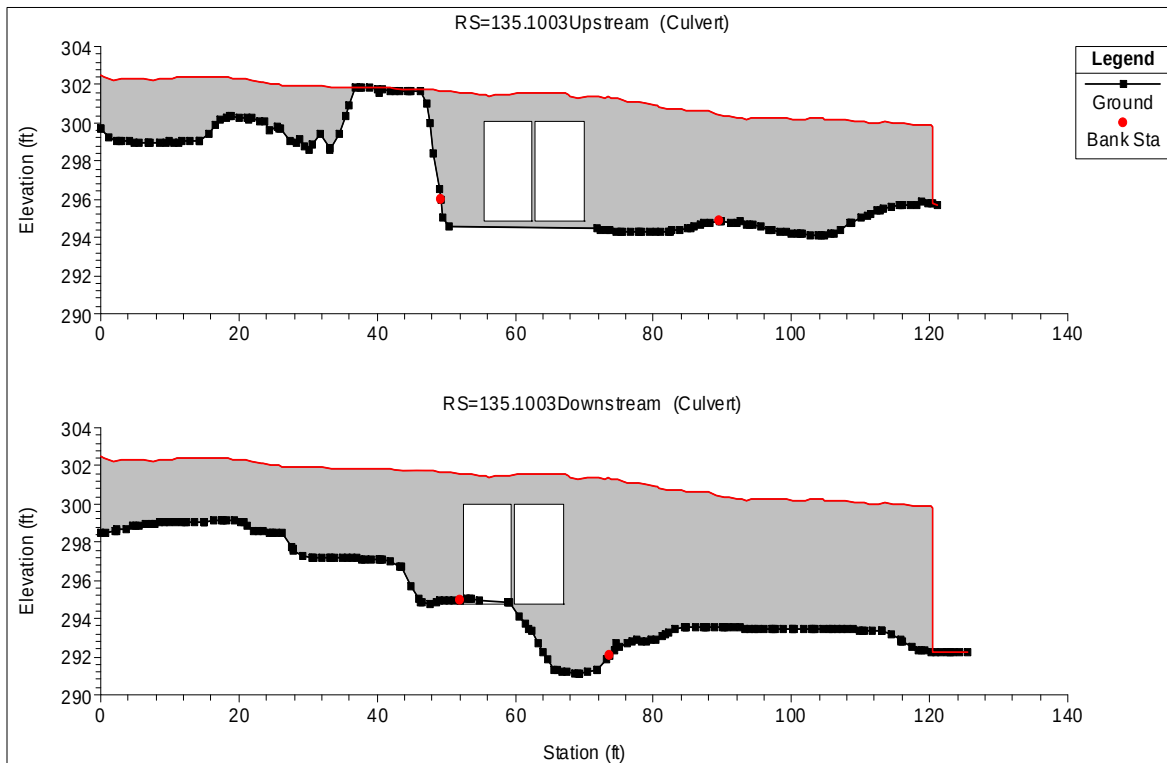


Figure C- 5. Keaau-Pahoa Road Culvert 2.

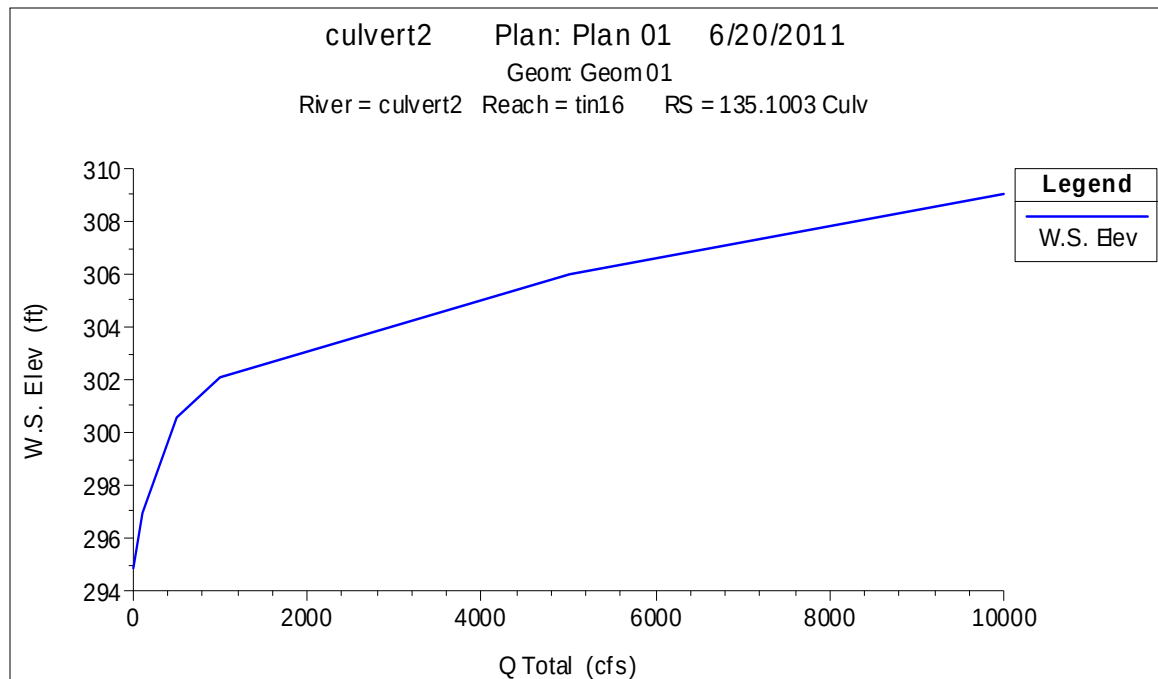


Figure C- 6. Rating Curve of Keaau-Pahoa Road Culvert 2.

3) Waipahoeohoe Stream Bridge

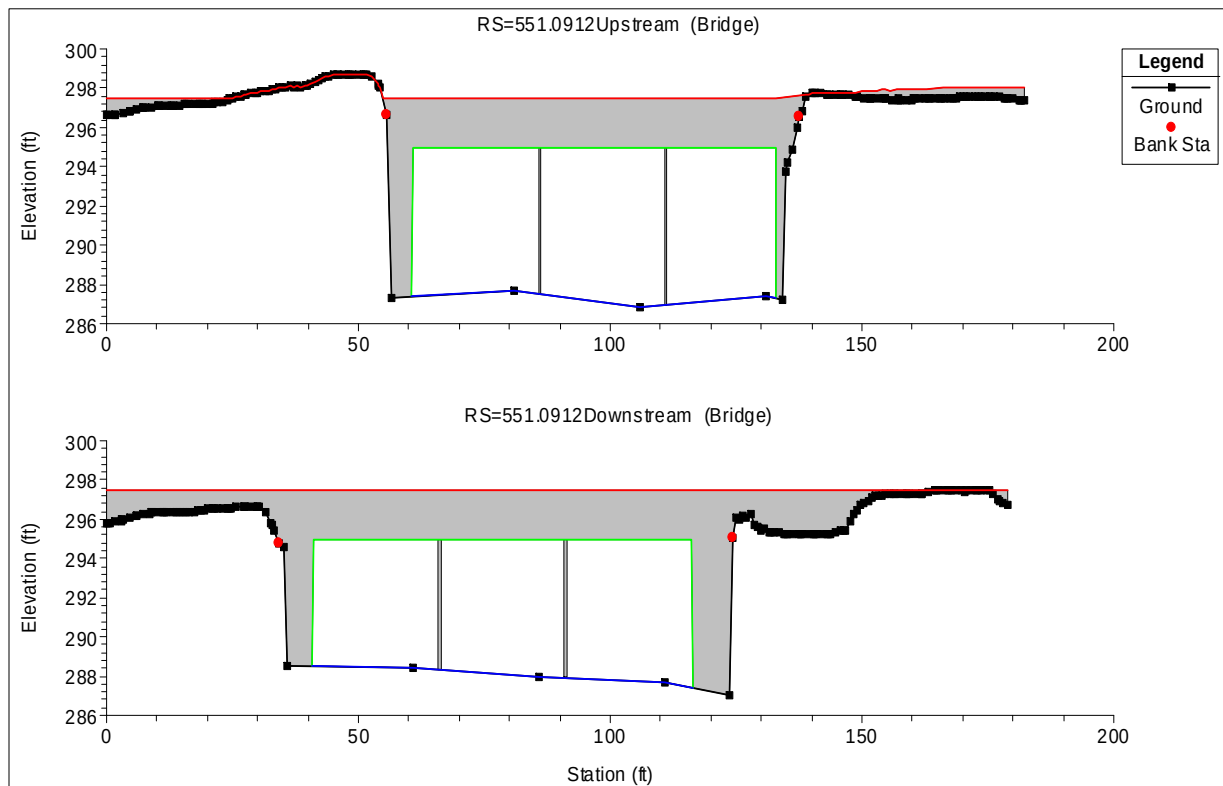


Figure C- 7. Waipahoeohoe Stream Bridge.

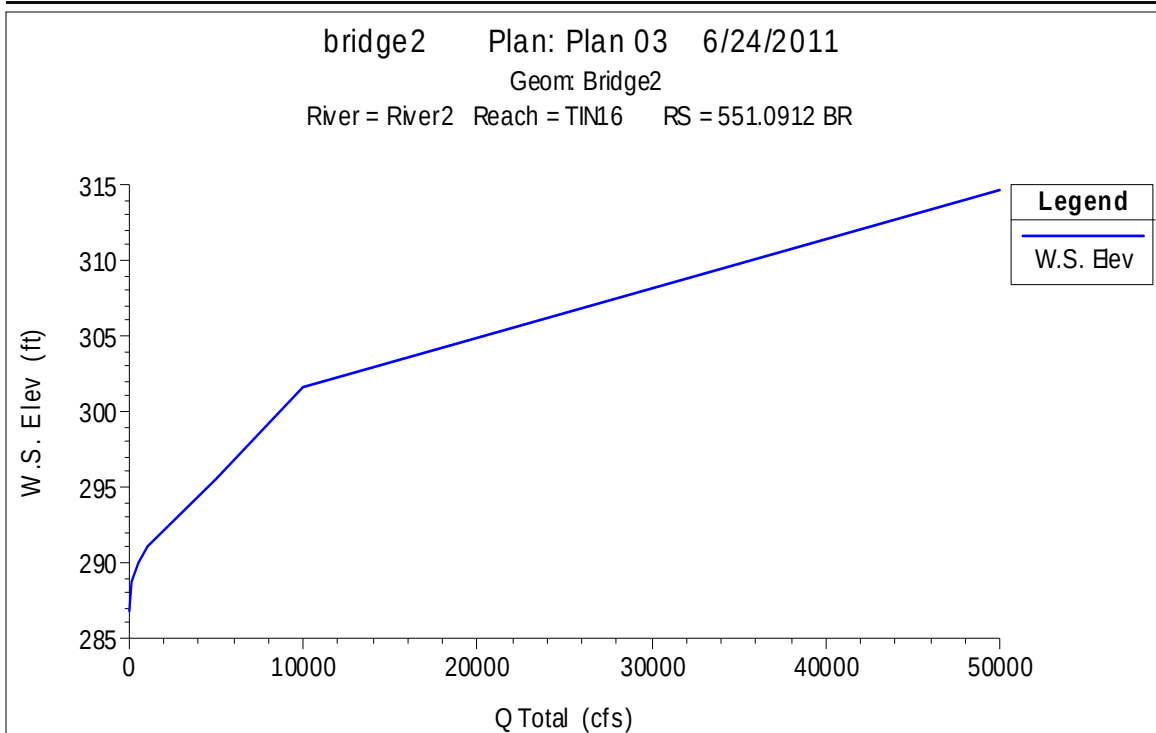


Figure C- 8. Rating Curve of Waipahoe Stream Bridge.

4) Moho Road Culvert 1



Figure C- 9. Photo of Moho Road Culvert 1.

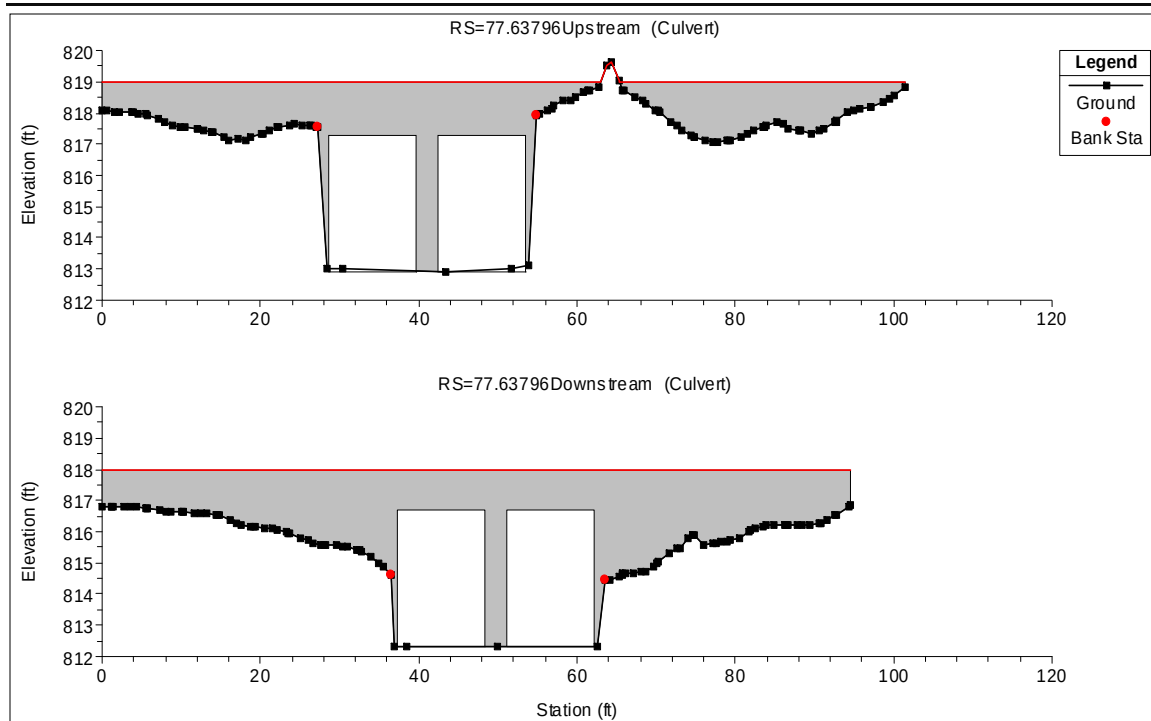


Figure C- 10. Cross-section of Moho Road Culvert 1.

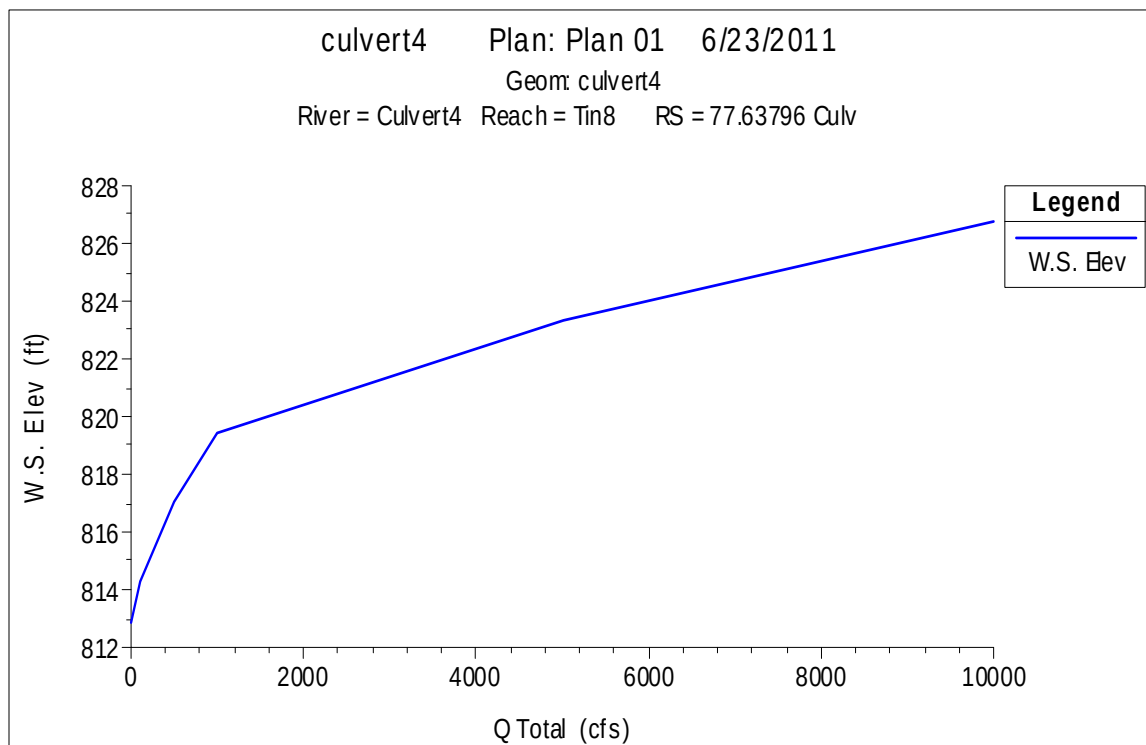


Figure C- 11. Rating Curve of Moho Road Culvert 1.



5) Moho Road Culvert 2



Figure C- 12. Photo of Moho Road Culvert 2 (Downstream side).

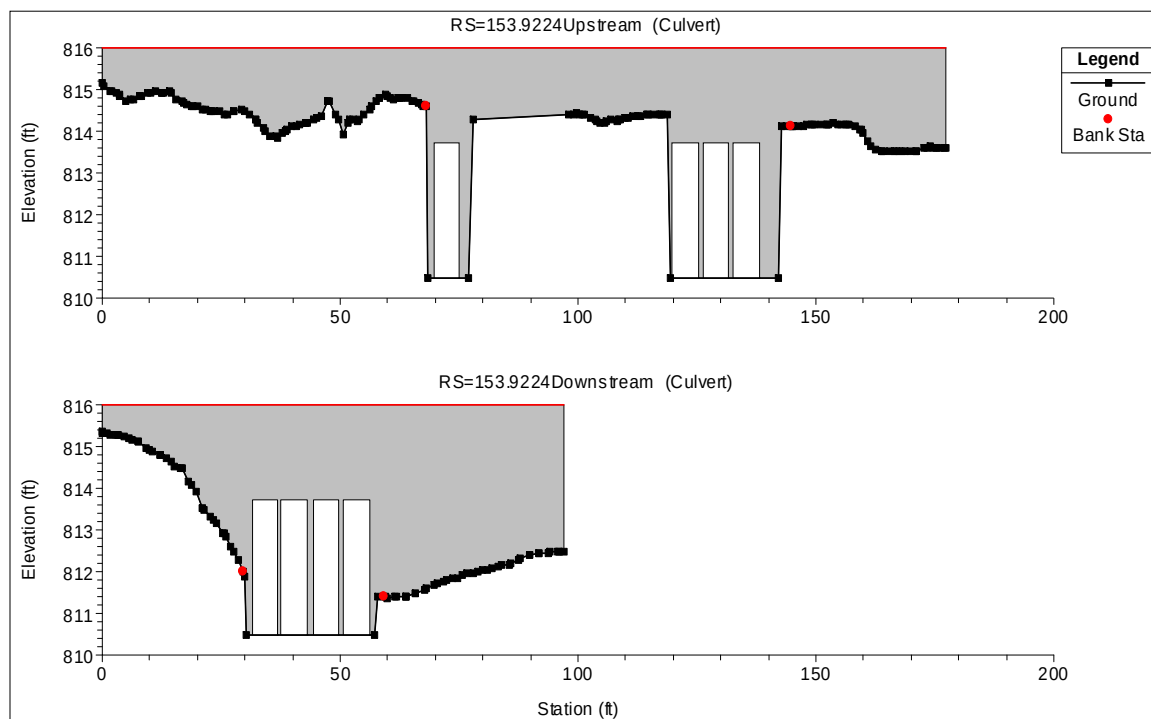


Figure C- 13. Cross-section of Moho Road Culvert 2.

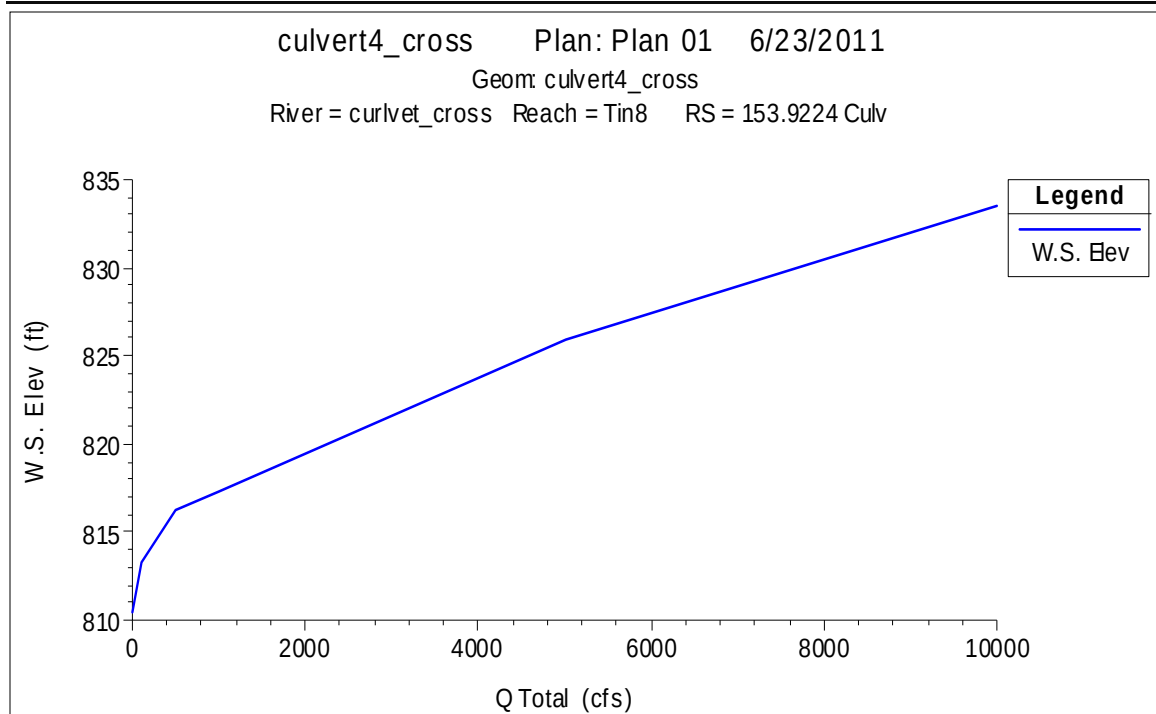


Figure C- 14. Rating Curve of Moho Road Culvert 2.

6) South Kūlani Road Bridge



Figure C- 15. Photo of South Kūlani Road Bridge.

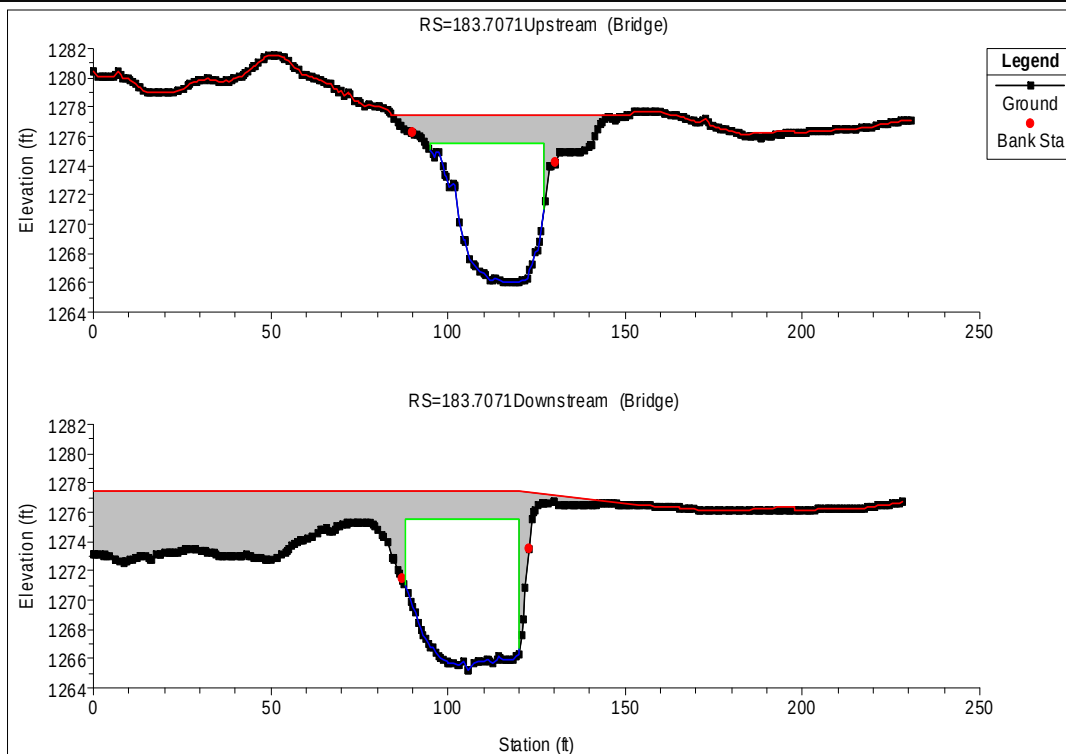


Figure C- 16. Cross-section of South Kūlani Road Bridge.

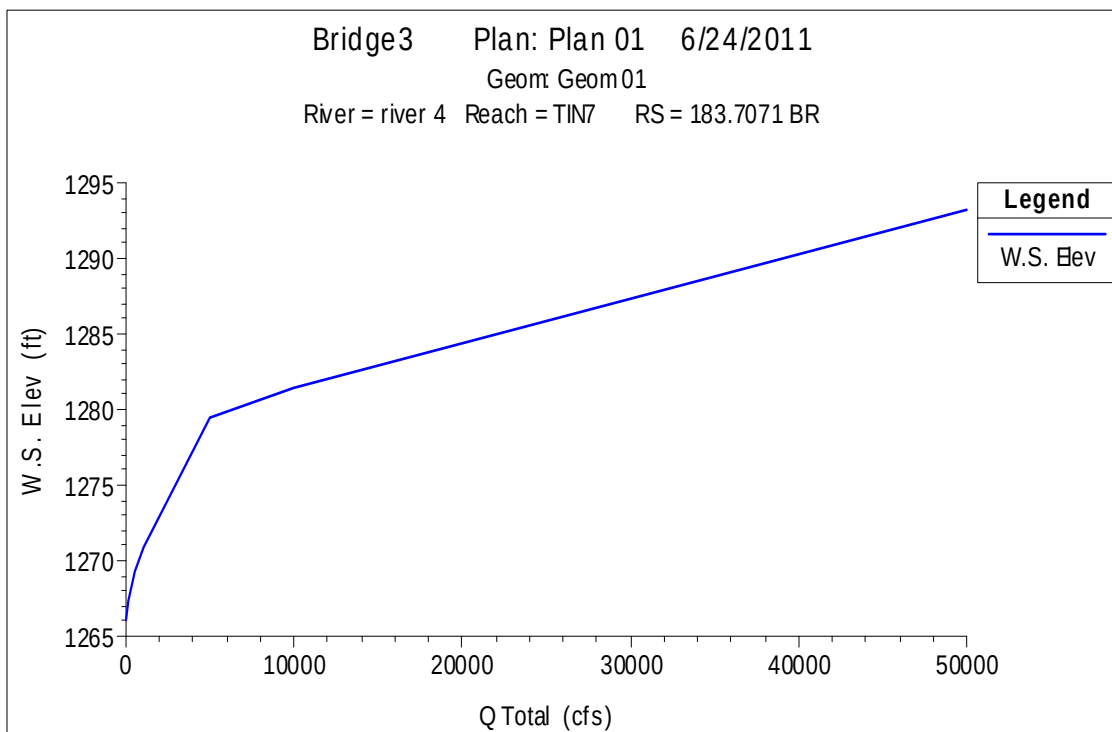


Figure C- 17. Rating Curve of South Kūlani Road Bridge.



7) Enos Road Culvert



Figure C- 18. Photo of Enos Road Culvert.

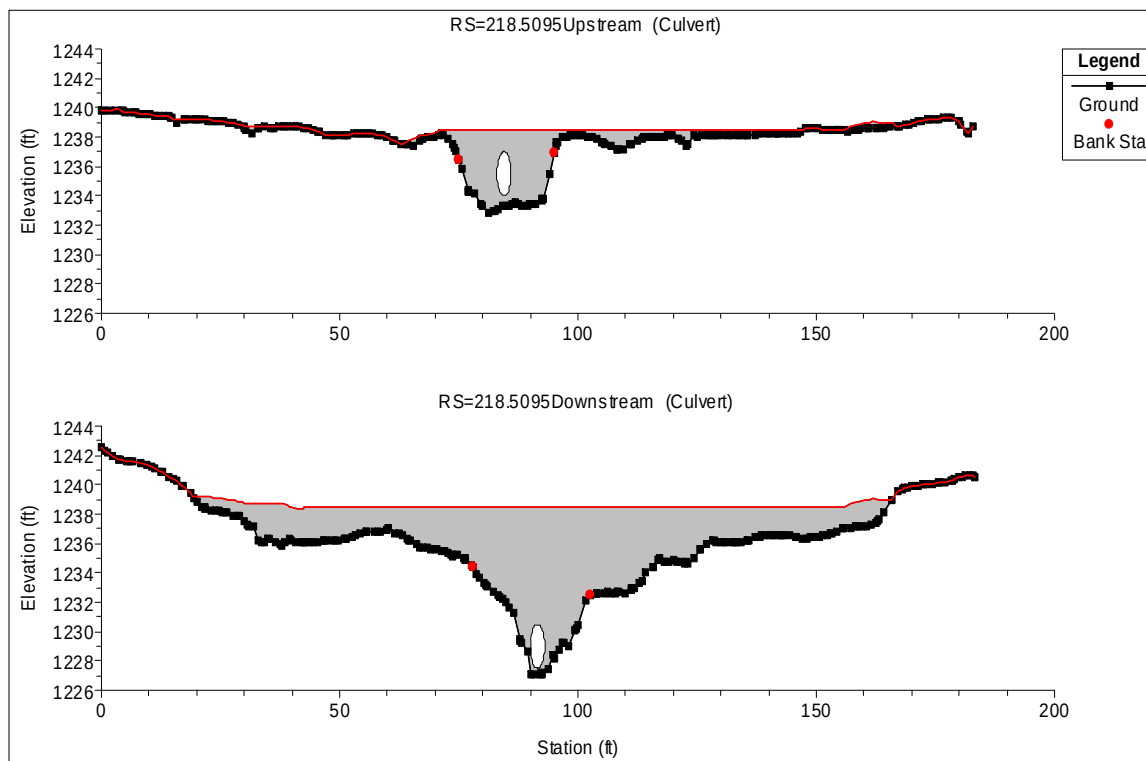


Figure C- 19. Cross-section of Enos Road Culvert.

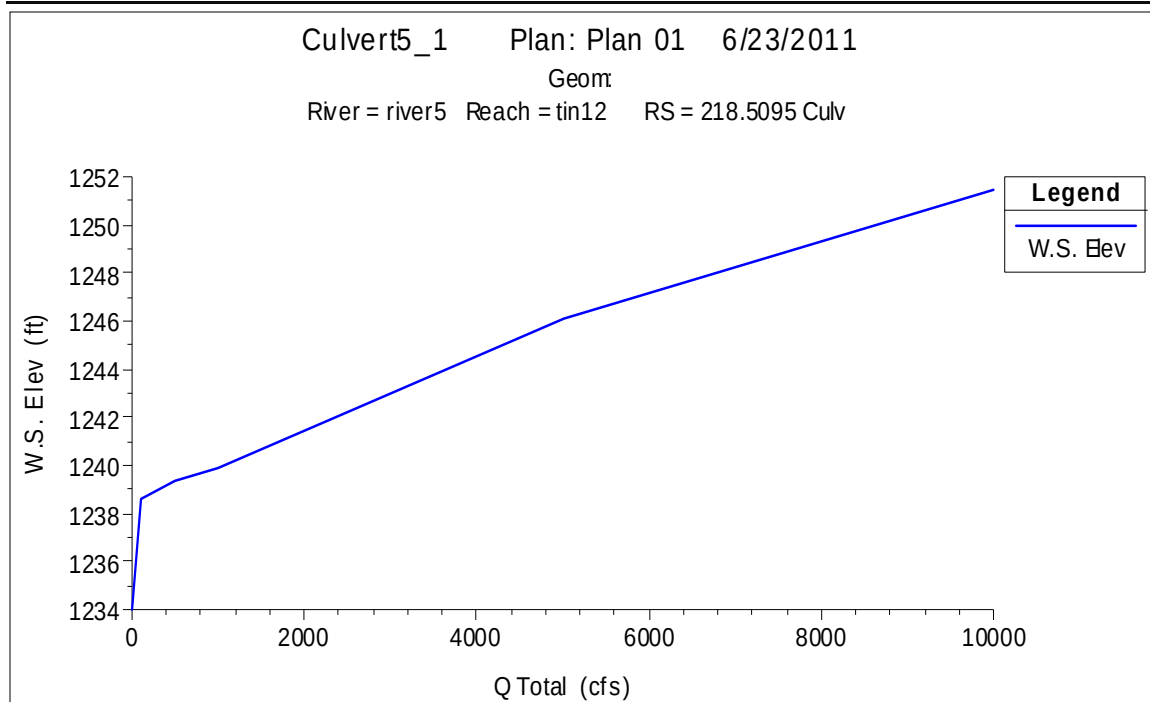


Figure C- 20. Rating Curve of Enos Road Culvert.

8) South Pszyk Road Culvert 1

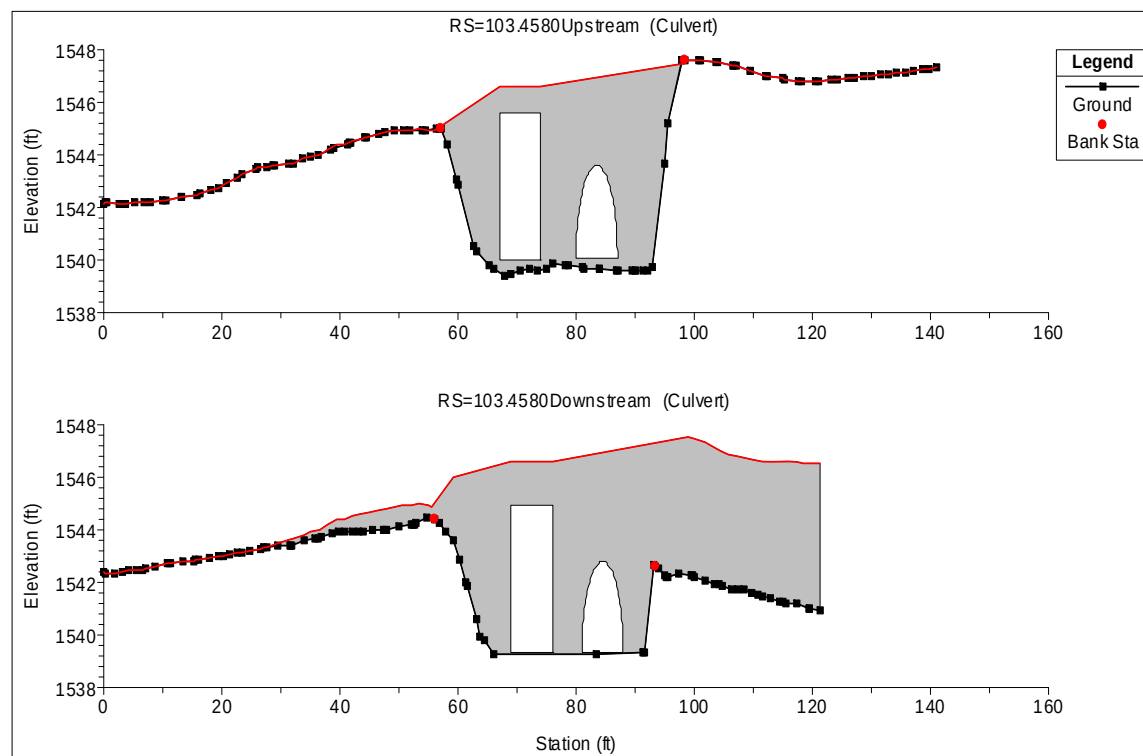


Figure C- 21. Cross-section of South Pszyk Road Culvert 1.

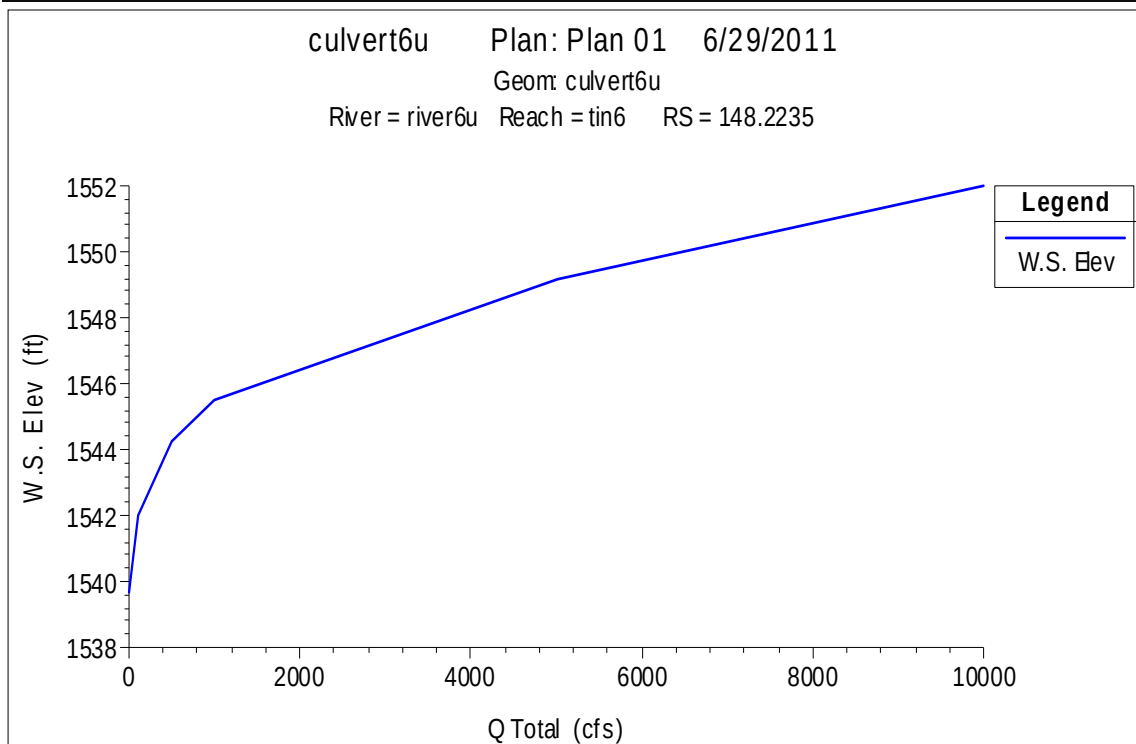


Figure C- 22. Rating Curve of South Pszyk Road Culvert 1.

9) South Pszyk Road Culvert 2



Figure C- 23. Photo of South Pszyk Road Culvert 2.

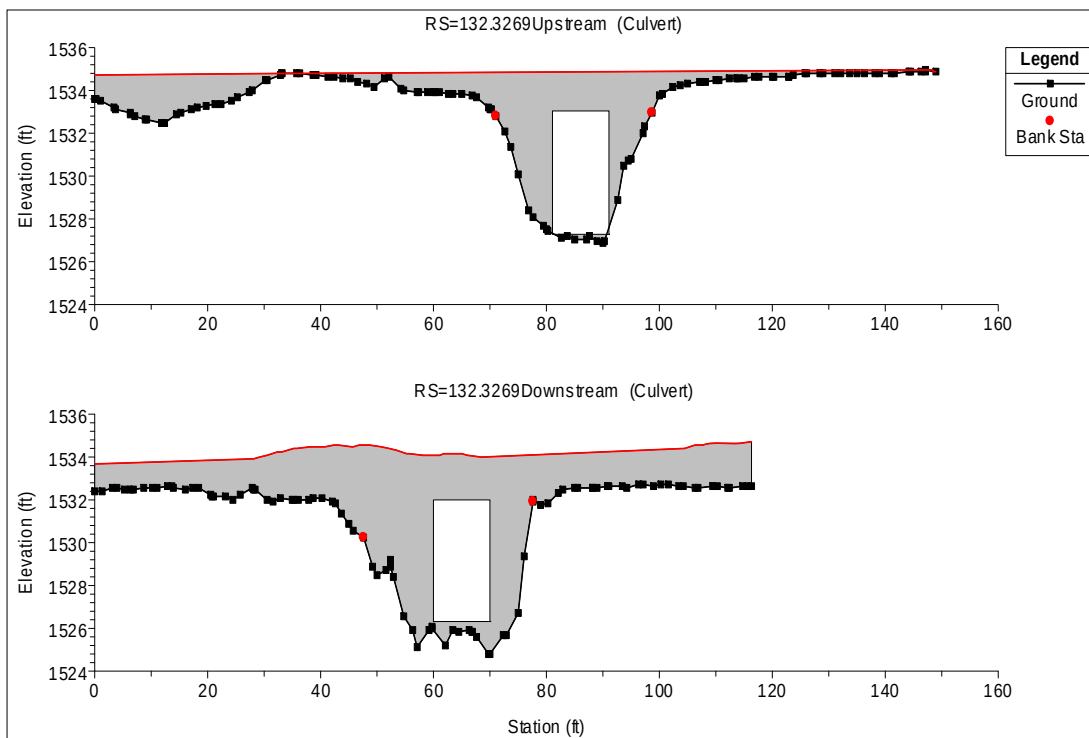


Figure C- 24. Cross-section of South Pszyk Road Culvert 2.

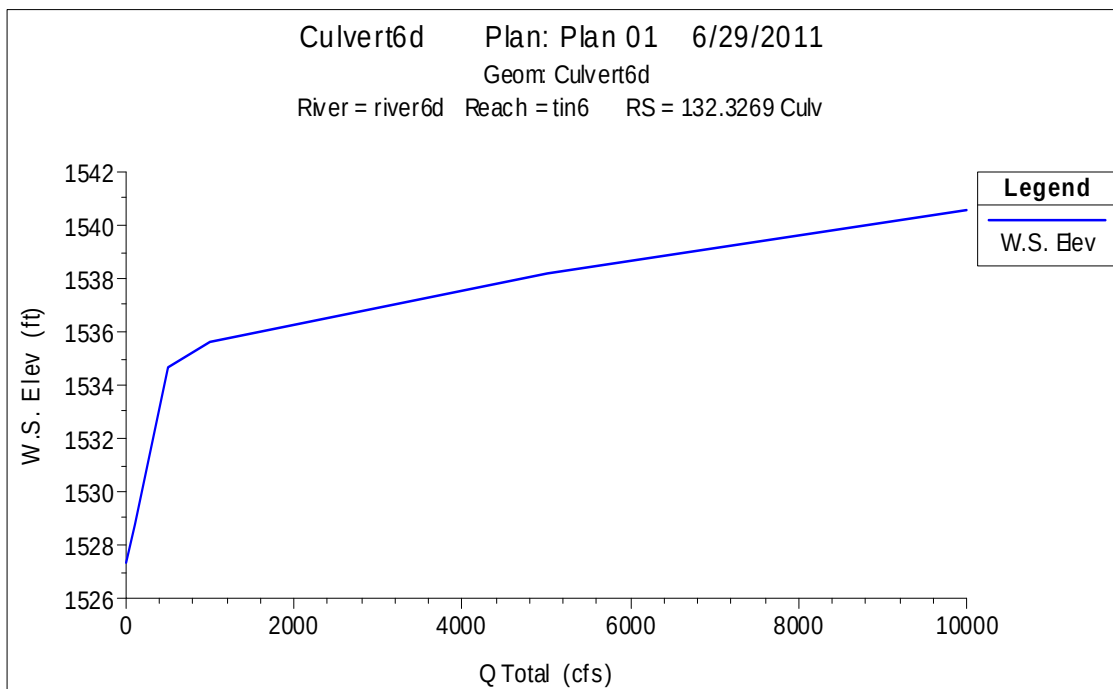


Figure C- 25. Rating Curve of South Pszyk Road Culvert 2.



10) South Kopua Road Bridge

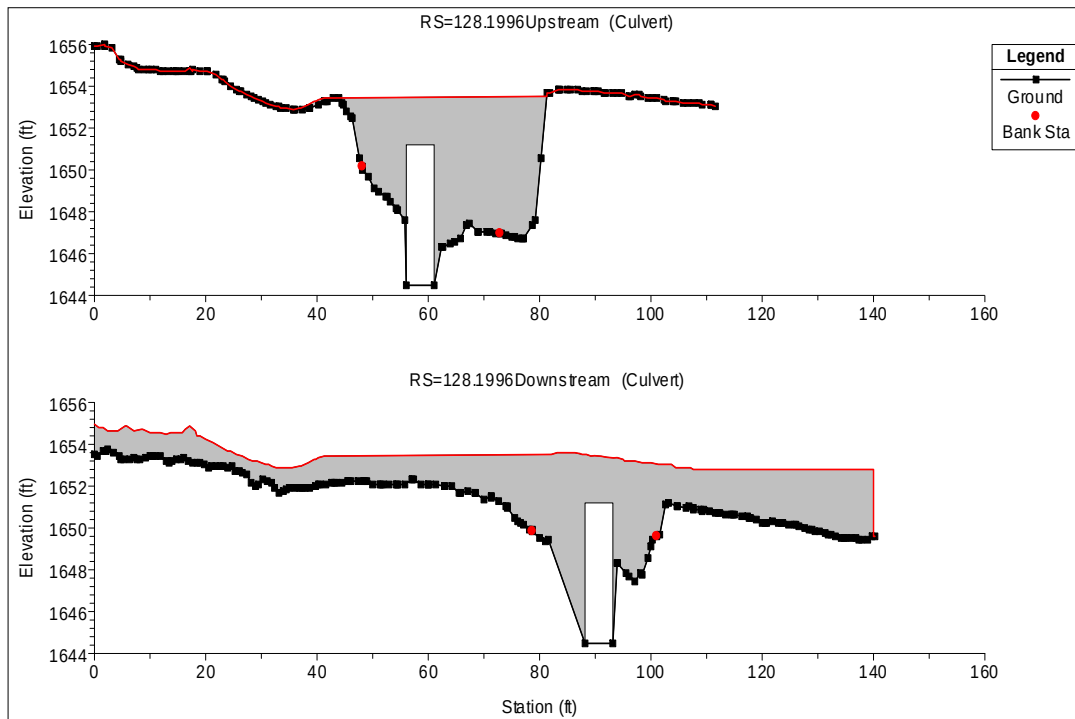


Figure C- 26. Cross-section of South Kopua Road Bridge.

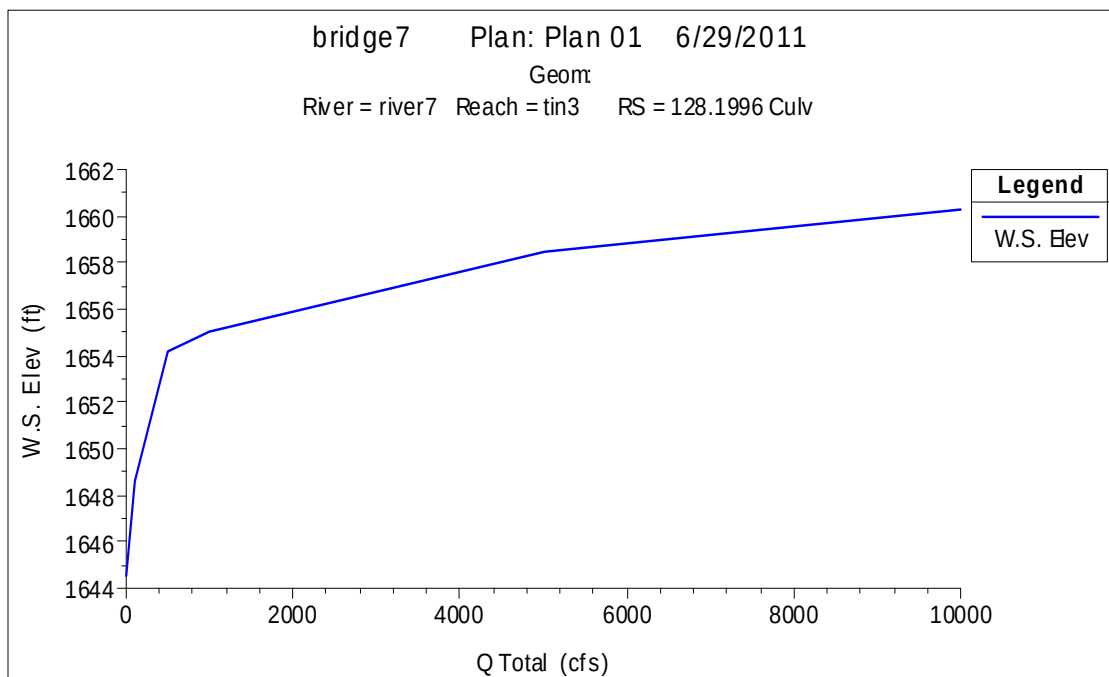


Figure C- 27. Rating Curve of South Kopua Road Bridge.



11) S. Kopua Road Culvert

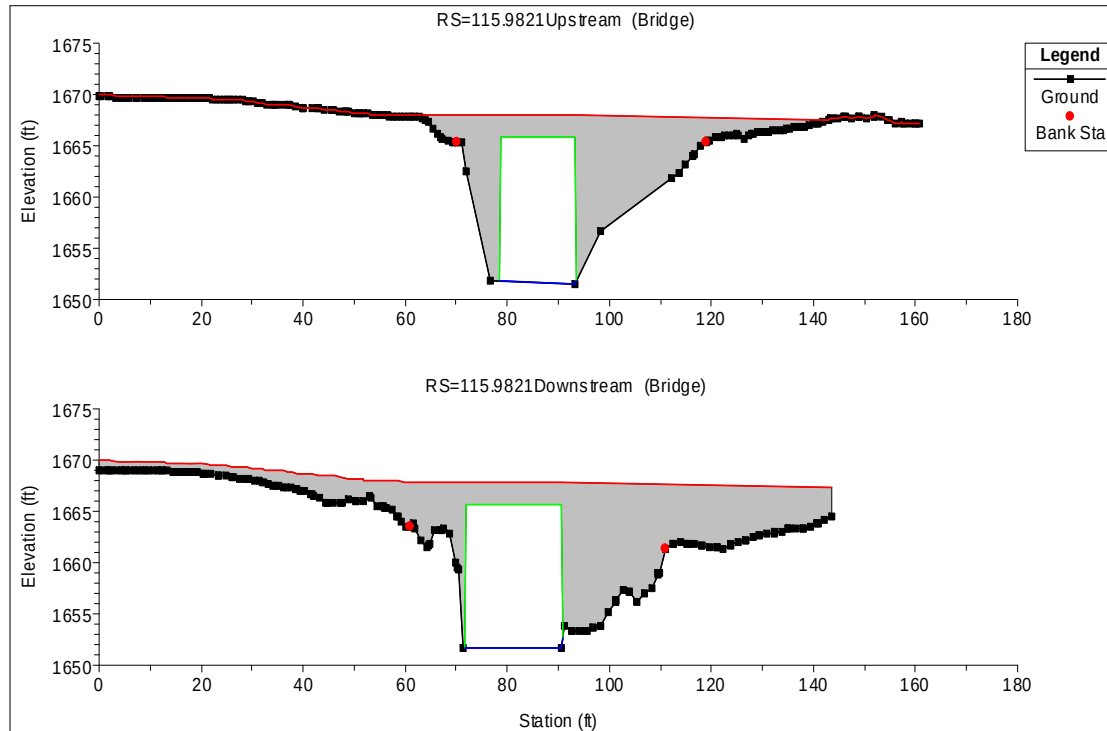


Figure C- 28. Cross-section of South Kopua Road Culvert.

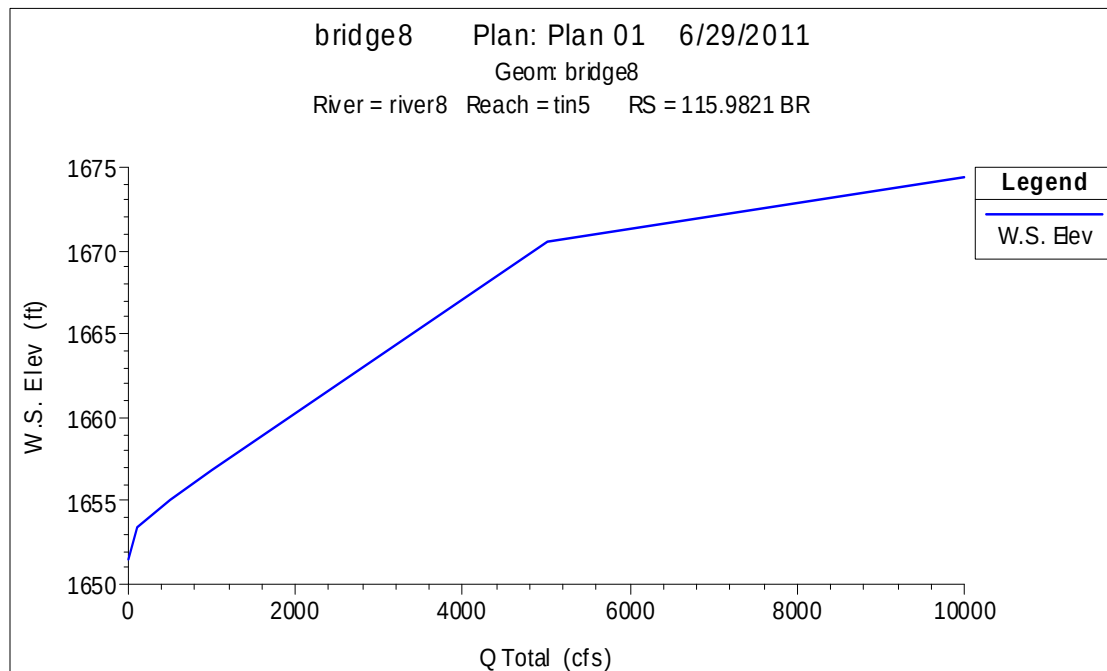


Figure C- 29. Rating Curve of South Kopua Road Culvert.



12) North Oshiro Road Bridge 2.



Figure C- 30. Photo of North Oshiro Road Bridge 2.

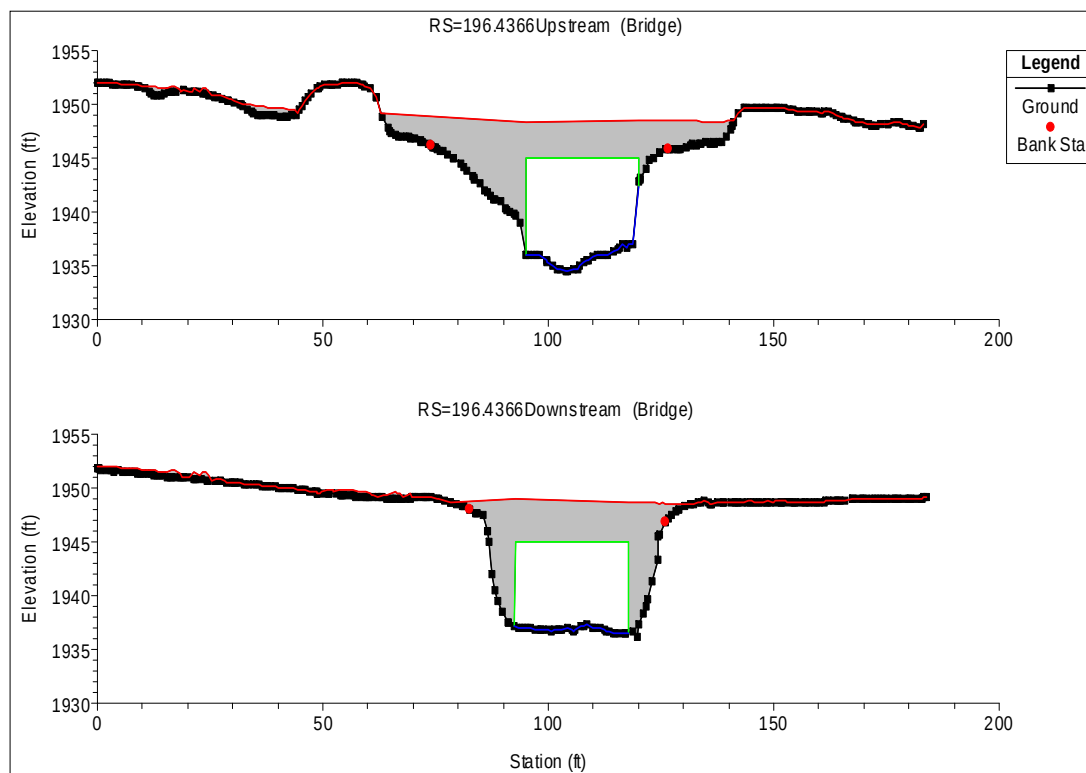


Figure C- 31. Cross-section of North Oshiro Road Bridge 2.

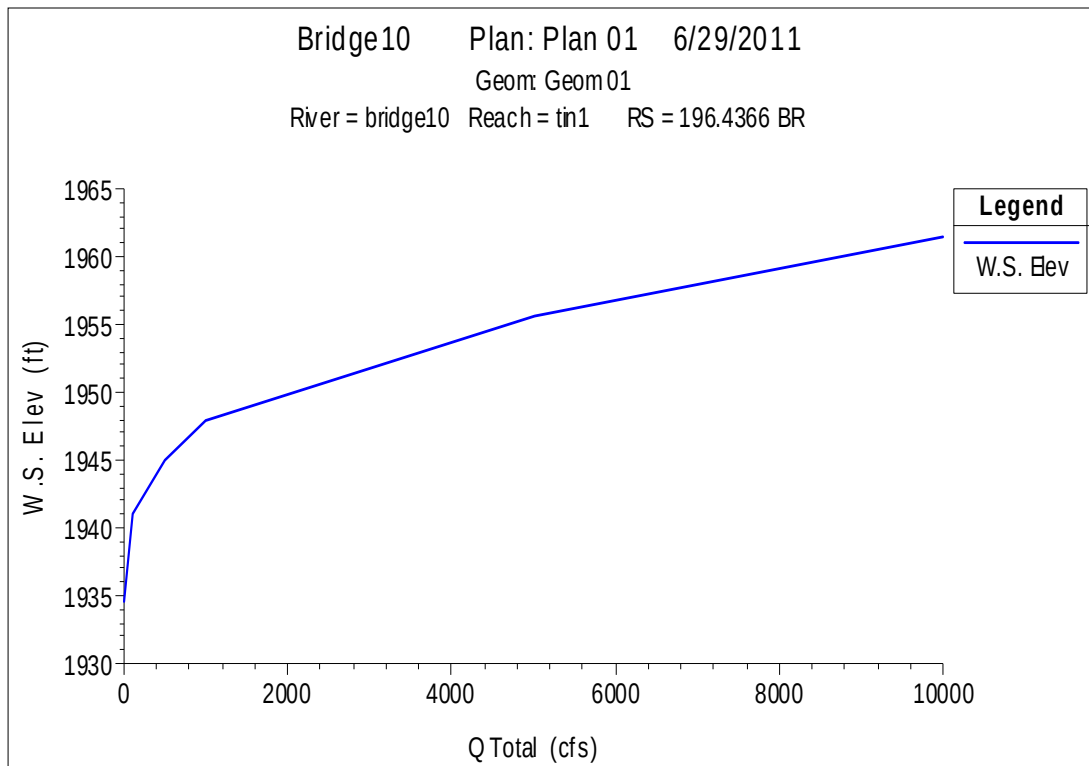


Figure C- 32. Rating Curve of North Oshiro Road Bridge 2.