HYDROLOGY AND HYDRAULICS STUDY
FLOOD OF OCTOBER 30, 2004
MANOA STREAM
HONOLULU, OAHU

16 November 2006
HYDROLOGY AND HYDRAULICS STUDY
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Prepared by
the Department of the Army
U.S. Army Corps of Engineers
Honolulu District
Fort Shafter, Hawaii

15 November 2006
# HYDROLOGY AND HYDRAULICS STUDY
## FLOOD OF OCTOBER 30, 2004
### MANOA STREAM
#### HONOLULU, OAHU

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Executive Summary

A post-flood analysis of the October 30, 2004 flood event was conducted using rainfall-runoff and stream hydraulic computer modeling. The stream hydraulics model was also used to determine the feasibility of several short-term flood mitigation measures. The October 30, 2004 flood, caused by a heavy and intense thunderstorm, was a significant flooding event in Manoa Valley. The high intensity rainfall storm caused flood waters to leave the stream channel by Manoa District Park and Woodlawn Drive Bridge and flood nearby residences and businesses as well as the University of Hawaii Manoa Campus. This devastating flood caused approximately $80 million of damages to University property in addition to $5 million of damages to about 120 homes.

Model results indicate that Manoa Stream, between Kahalo Drive and Woodlawn Drive has insufficient channel capacity to contain the flood waters caused by the October 30, 2004 storm. Flood damage was further aggravated by debris blockage of the East Manoa Road and Woodlawn Drive bridges. Frequency analysis using the rainfall-runoff model estimated the October 30, 2004 flood event to be about a 4 percent chance or 25-year flood event. An analysis of bridge and channel capacities determined that Manoa Stream can safely carry about 4,500 to 5,000 cubic feet per second (cfs) within the banks, but the East Manoa Road and Woodlawn Drive Bridges can only safely pass flows in the range of 2,800 to 3,900 cfs without debris blockages. Flows in this range have a magnitude less than the 10 percent chance or 10-year flood.

Alternatives analyzed included levees or floodwalls along selected portions of the stream channel between Manoa District Park and Woodlawn Drive and creating an artificial channel between East Manoa Road and Woodlawn Drive. Of these alternatives, the channel drop structure at Woodlawn Drive Bridge has the best potential for increasing the capacity here in the short-term with the least amount of maintenance, aesthetic, bridge structure, and drainage problems to mitigate. Larger discharges on the order of a 2 percent chance or 50-year flood would still cause over bank flooding regardless of the short-term alternative. New high resolution topographic data would allow a more detailed analysis of the channel drop structure as well as a re-evaluation of the Flood Insurance Study 100-year floodplain.
Introduction

A significant flooding event occurred in Manoa Valley on the evening of October 30, 2004 due to a heavy and intense thunderstorm. The high intensity rainfall storm caused flood waters to leave the stream channel by Manoa District Park and Woodlawn Drive Bridge and flood nearby residences and businesses as well as sending a significant amount of water that flooded areas outside of the Flood Insurance Rate Map (FIRM) 100-year mapped floodplain from Noelani Elementary School to the University of Hawaii Manoa Campus. This devastating flood caused approximately $80 to $90 million of damages to University property in addition to damages to about 120 homes.

Purpose and Scope

This report describes a post-flood analysis of the October 30, 2004 flooding event through the use of computer rainfall-runoff and stream hydraulic modeling to determine the feasibility of several short-term flood mitigation measures. To recreate the October 30, 2004 runoff magnitude, the U.S. Army Corps of Engineer’s (USACE) rainfall-runoff model, Hydrologic Engineering Center-Hydraulic Modeling System (HEC-HMS), was used with observed rainfall and stream flow data collected by the National Weather Service (NWS) and U.S. Geological Survey (USGS). The calibrated rainfall-runoff model was also used to evaluate previous estimates of the 10, 4, 2, and 1 percent chance exceedance floods (10-, 25-, 50-, and 100-year floods, respectively). The stream hydraulic model was used to recreate the Manoa Stream flood event from the Kahaloa Drive Bridge to the Woodlawn Drive Bridge using the stream reach by Kanewai Field as the downstream boundary condition. The USACE hydraulic model, Hydrologic Engineering Center-River Analysis System (HEC-RAS), was used to recreate the flood event and evaluate the feasibility of several flood mitigation measures. Existing topographic, existing and new stream cross-section, and existing bridge and road geometry data was used to create the models.

New data consisted of post-flood field site visits, high water marks obtained from the flood event, and stream cross-sectional data collected by the USGS and the City and County of Honolulu (C&C). This report does not evaluate the costs or impacts on sedimentation and aquatic life of any of the modeled alternatives. It is not the intent of any alternative to provide protection from the 1 percent chance or 100-year flood. Debris mitigation is not specifically addressed except that such measures will help prevent bridge blockages. No alternatives into flooding problems along Manoa Stream upstream of Kahaloa Drive Bridge and downstream of Woodlawn Drive Bridge were studied. No detailed analysis into the drainage, structural, aesthetic, or maintenance issues created by any of these possible flood mitigation alternatives was conducted.

This study was funded by the U.S. Army Corps of Engineers Flood Plain Management Services Program and conducted in cooperation with the State of Hawaii, Department of Land and Natural Resources (Engineering Division) and the City and County of Honolulu, Department of Design and Construction (Civil Division).
Acknowledgments

The assistance of Tim Trang and Marvin Char, Department of Design and Construction, City and County of Honolulu, Eric Hirano and Sterling Yong (retired), State of Hawaii Department of Land and Natural Resources, Glen Oyama, Honolulu Board of Water Supply, Tammy Makizuru-Higa, State of Hawaii Civil Defense, and Barry Hill, U.S. Geological Survey, in obtaining plans, photos, and data is gratefully acknowledged.

Study Area

The Island of Oahu is formed by the eroded remnants of two elongated shield volcanoes, the Waianae and Koolau. Manoa Valley is a relatively wide valley on the Leeward side of the Koolau Range (Figure 1). The upper portion of the valley consists of Koolau Basalt along the headwaters with sedimentary deposits and later Honolulu Volcanics in the middle and lower valley (Hunt, 1996). Soils in the study area consist mostly of well drained silty clays predominately from the Lolekaa series in the headwaters and middle valley, Hanalai silty clays in the middle valley, and silty clay loams of the Tantalus and Makiki series in the lower valley (Foote and others, 1972).

The climate of Oahu is warm and humid. Average annual temperature near the study area is about 75°F and monthly averages range from 64°F to 84°F (Owenby and Ezell, 1992). The distribution of rainfall is affected by the prevailing northeasterly trade winds and the topography of the island. Because of the Koolau Range, which has an altitude of 2,000 to 3,000 ft above mean sea level, there is orographic lifting and cooling of marine air masses moving with the trade winds which result in heavier and more frequent rainfall on the windward side and near the crest of the Koolau Range. Mean annual rainfall in Manoa Valley varies from 40 inches in the lower valley to 160 inches in the headwaters (Giambelluca and others, 1986). Streamflow is perennial and shows a rapid response to rainfall with short times to peak.

Manoa Stream, with a drainage area of about 7 square miles, begins in the Koolau Mountain range as a heavily forested natural stream and changes into an urban stream that is highly modified and controlled. Portions of the urban stream are lined with concrete and some banks are stabilized with concrete masonry walls. The hydrologic model included a 6 square mile area of the Manoa Stream valley from the Koolau crest to Kanewai Field (Figure 1). The hydraulic model included a section of Manoa Stream from about 800 ft upstream of the Kahaloa Drive Bridge to about 700 feet downstream of the wooden foot bridge at Kanewai Field (Figure 2).
Figure 1 - Upper Manoa Watershed
Hydrology and Hydraulics Study
Flood of October 30, 2004
Manoa Stream, Oahu, Hawaii
Flood History

Based on historical flood damages, the flood of October 30, 2004 was the most devastating in terms of dollar amount in Manoa Valley. Not much is known of the early flood history in Manoa Valley except for two known deaths by drowning: one during the storm on December 3, 1918 where the "Manoa Upper" gage station, recorded 5.7 inches of rain and 53 mph winds and the other during the storm on December 3, 1950 where the "Manoa Tunnel" gage recorded 6.1 inches of rain (M&E Pacific, Inc., 1977). Based on a history of flood peaks recorded in the back of Manoa Valley for two tributary streams to Manoa Stream, the storm of January 16, 1921 caused the maximum flood peaks to be recorded at the long-term USGS stream gaging stations. Peak flows were 3,250 cfs and 3,090 cfs at station 16238500 Waihi Stream which was operated from 1915 to 1982 and station 16240500 Waiakeakua Stream which has record from 1913 to present. Combined peak flow would be about 6,340 cfs at the stream junction downstream of both gages. Heavy rains in May 1927 caused about $23,000 of damage to about 50 farms in the valley. The flood on February 4, 1965 caused streams in Manoa and Palolo Valleys to record the highest peaks since 1921 (Hoffard, 1965) and the storm on November 14-15, 1965 flooded homes in the vicinity of Kanewai-Koali Road. The Flood of December 17-18, 1967 caused damage to Waikiki as the Ala Wai Canal overflowed but no flooding was reported in Manoa Valley. Rainfall for this storm recorded in Palolo Valley was 10.06 inches in 8 hours and 2.4 inches in 1 hour. A peak flow of 10,100 cfs was determined at the Manoa-Palolo Drainage Canal (Department of the Army, 1968). Flooding on the University of Hawaii Campus was recollected as causing gulley erosion by the Hawaii Institute for Geophysics building (Oral Communication comment at Manoa October 2004 Halloween Flood Symposium, February 28, 2005). Two other storms causing flooding in Manoa Valley were recorded in December 1992 where Manoa Stream overtopped the stream bank and flowed over Woodlawn Drive and on March 24, 1994 when 12.5 inches fell in 24 hours and some flooding occurred when a tree blocked the Woodlawn Drive Bridge.

The October 30, 2004 Storm

According to the National Weather Service (NWS) at website http://www.prh.noaa.gov/hnl/pages/events/ManoaFlood20041030/, last accessed on November 2, 2005, an unstable atmosphere due to an upper level low resulted in the development of heavy showers and thunderstorms near Oahu. During the late afternoon, an area of showers was pushed over southeast Oahu by low level tradewinds. These showers developed into a thunderstorm that remained stationary due to the terrain and produced very heavy rainfall in the headwaters of Manoa Valley in a very short time. Peak rainfall intensity was 3.72 inches in 1 hour and 8.71 inches in 6 hours according to the NWS. The resulting runoff overflowed the banks of Manoa Stream at about 7:45pm by Manoa District Park sending floodwaters through homes and down Woodlawn Drive through Noelani School and the University of Hawaii campus (Figures 2 and 3).
Figure 3 - Floodplain Map
Hydrology and Hydraulics Study
Flood of October 30, 2004
Manoa Stream, Oahu, Hawaii
Rainfall Data

Rainfall data for the October 30, 2004 flood was recorded at various sites in Manoa Valley by the NWS, U.S. Geological Survey (USGS), and Honolulu Board of Water Supply (BWS) (Figure 1). The NWS gage located at Lyon Arboretum recorded a total of 3.72 inches in 1 hour and 8.71 inches in a 6-hour span from 2:00 to 8:00 pm. The 24-hour rainfall total at this site was 10.08 inches. The USGS rain gage located in the lower valley at Kanewai Field recorded a 24-hour rainfall total of 1.67 inches. The BWS rain gage located in the upper valley at the BWS Manoa Tunnel recorded 11.14 inches in 24-hours. This gage, although normally a recoding gage, did not record rainfall throughout this storm. Gages in Palolo Valley recorded lower rainfall totals, the BWS Palolo Tunnel gage recorded 6.22 inches in 24 hours while the USGS gage on Pukele Stream recorded 4.07 inches in 24 hours. Rainfall data for the recording gages in 15 minute increments are listed in Table 1.

Data from the NWS and BWS gages were computed from raw data values supplied by the NWS and BWS. The NWS data is available from their Hydronet system, a network used primarily for flood forecasting, so data are not quality assured. The data start from 1995 and can only be found at website http://www.prh.noaa.gov/hnl/pages/hydrology.php (last accessed on September 14, 2004) (Kevin Kodama, Senior Staff Hydrologist, NWS, oral communication, 2004).

Streamflow Data

Peak streamflow data was collected by the USGS and U.S. Army Corps of Engineers (USACE) and total streamflow over the storm at the USGS stream gage on Waiakeakua Stream (station 16240500). The USGS operated three gages along Manoa Stream, station 16240500, 16241500 Manoa Stream at Lowrey Ave Bridge, and station 16242500 Manoa Stream at Kanewai Field (Figure 1). Peak streamflows at 16240500, 16241500, and 16242500 were 1,100 cubic feet per second (cfs), 5,050 cfs, and 5,870 cfs, respectively (Data available from USGS website at http://hi.water.usgs.gov/, last accessed on November 2, 2005). The USACE measured three high water marks (Photos 1 and 2) along Woodlawn Drive and, using the road plans provided by the City and County of Honolulu (C&C), determined the peak streamflow down Woodlawn Drive to Noelani Elementary School to be 2,000 cfs by slope-area indirect measurement method (Dalrymple and Benson, 1967; Fulford, 1994). Sensitivity analysis of this slope-area measurement to account for error in the high water marks, parked vehicles as obstacles, and variation in Manning’s n roughness values created a range of possible discharges from 1,500 to 2,600 cfs. The value of 2,000 cfs was used for the hydraulic modeling analysis.
Table 1. Rainfall Data in inches from recording rain gages in Manoa and Palolo Valleys, Oahu, Hawaii, October 30 to 31, 2004

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<tr>
<td>31-Oct-04</td>
<td>03:30</td>
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</table>
Photo 1. Debris line high water mark on fence, Agricultural Station, Woodlawn Drive, Manoa Valley, November 2, 2004.

Photo 2. Debris line high water mark on slope, Woodlawn Drive, Manoa Valley, November 2, 2004.
Flood Damages

According to data collected by State of Hawaii Civil Defense, residents and businesses in Manoa Valley suffered about $5 million of damage from flood waters. Of this total, business damages totaled $122,350. The bulk of the damages were residential damages. The estimated damages to the University of Hawaii Campus has gone as high as $100 million but has lately been reported to be $81 million (Honolulu Advertiser, May 4, 2005). State of Hawaii Civil Defense reports a total damage estimate for property of the State of Hawaii of $70.7 million. Many photos of the flood damages are available on the internet. One such webpage highlighting the damage to the University of Hawaii with links to other photos is http://www.hawaii.edu/ala/flood.php (last accessed November 21, 2005).

Hydrologic Modeling

The rainfall-runoff model for this storm was done using the USACE rainfall-runoff model HEC-HMS version 2.2.2 (U.S. Army Corps of Engineers, 2001). Required input data for the HEC-HMS model includes basin characteristics such as drainage area, unit hydrograph parameters, soil infiltration rates, stream flow routing parameters and rainfall amounts. To replicate the October 30, 2004 storm, the recorded 15 minute interval rainfall data from the Lyon Arboretum and Kanewai Field rain gages was used (Table 1, Figure 1) along with the storm total of 11.14 inches at the BWS Manoa Tunnel rain gage (Figure 1). For a flood-frequency computation, the assumption that the derived flood frequencies are approximately equal to the frequency of the design rainfall (U.S. Army Corps of Engineers, 2002a) is made. A 5 minute time step was used for all model computations. The model schematic is shown in Figure 4.

The model was calibrated using the recorded rainfall from the Manoa Valley rain gages listed above and streamflow data from USGS station 16240500 on Waiakeakua Stream, the only gage in Manoa Valley that had a complete record of the October 30 flood event. The model used the initial/constant method for infiltration losses and Snyder’s Unit Hydrograph method for runoff calculations. The drainage area of the model covered Manoa Valley from the Koolau Crest to Manoa Stream at Kanewai Field, about 6 square miles in 6 sub-basins and calibrated Snyder’s Unit Hydrograph parameters determined at the station 16240500 sub-basin were used at all the other sub-basins (Tables 2 and 3; Figures 1 and 3). The soil infiltration factors for the Waihi Stream sub-basin (Table 2) was made slightly lower to account for the area of heavy rainfall over that sub-basin. Rick Fontaine of the USGS felt that the peak at station 16238500, Waihi Stream, was probably 25 percent higher than at 16240500 (Hydrologist, USGS, Oral communication, Manoa October 2004 Halloween Flood Symposium, February 28, 2005).
A comparison of peak streamflow data greater than 500 cfs recorded on the same date at the USGS stations 16238500 and 16240500 when both gages were in operation from 1915-1983, (Table 4) shows that the peaks at station 16238500 are generally lower by 14 percent on average. Therefore, the peak at Waihi Stream was made only slightly higher than at Waiakeaakua Stream. The soil infiltration parameters were also lowered to allow a better match to the peak flow at Lowrey Avenue Bridge (Junction 2). These values were then used for the remaining sub-basins. The drainage area for sub-basin 6, Kanewai, was determined to be about 1.07 square miles using Geographical Information Systems (GIS) software but was increased to 1.67 square miles (Table 3) to correspond to the USGS determined drainage area of 5.99 square miles. This drainage area size accounts for the storm drainage system of the University of Hawaii at Manoa campus (Lisa Miller, Hydrologist, USGS, Oral Communication, 2002). Routing was done by the lag method. Reach lag times were 10, 5, and 15 minutes for reaches 1, 2, and 3, respectively (Figure 4).
### Table 2. HEC-HMS Model Sub-basin Input Parameters for Manoa Stream, Flood of October 30, 2004, Oahu, Hawaii

<table>
<thead>
<tr>
<th>Sub-Basin</th>
<th>Name</th>
<th>Soil Infiltration Parameters</th>
<th>Snyder's Unit Hydrograph Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Initial (inch)</td>
<td>Constant (inch)</td>
</tr>
<tr>
<td>1</td>
<td>Waihi</td>
<td>1.1</td>
<td>0.9</td>
</tr>
<tr>
<td>2</td>
<td>Waiakeakua</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>3</td>
<td>Lowery</td>
<td>1.2</td>
<td>0.9</td>
</tr>
<tr>
<td>4</td>
<td>Park</td>
<td>1.2</td>
<td>0.9</td>
</tr>
<tr>
<td>5</td>
<td>Woodlawn</td>
<td>1.2</td>
<td>0.9</td>
</tr>
<tr>
<td>6</td>
<td>Kanewai</td>
<td>1.2</td>
<td>0.9</td>
</tr>
</tbody>
</table>

### Table 3. Sub-basin Drainage Areas and Raingage Weighting Percentages Used in HEC-HMS Model, Flood of October 30, 2004, Manoa Stream, Oahu, Hawaii

<table>
<thead>
<tr>
<th>Sub-basin</th>
<th>Description</th>
<th>Drainage area in square miles</th>
<th>Raingage weighting percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Lyon Arboretum</td>
<td>Manoa Tunnel</td>
</tr>
<tr>
<td>1</td>
<td>Waihi</td>
<td>1.14</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>Waiakeakua</td>
<td>1.06</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>Lowery</td>
<td>1.75</td>
<td>0.9</td>
</tr>
<tr>
<td>4</td>
<td>Park</td>
<td>0.14</td>
<td>0.9</td>
</tr>
<tr>
<td>Junction 2</td>
<td>Total area 1-4</td>
<td>4.09</td>
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</tr>
<tr>
<td>5</td>
<td>Woodlawn</td>
<td>0.23</td>
<td>0.7</td>
</tr>
<tr>
<td>6</td>
<td>Kanewai</td>
<td>1.67</td>
<td>0.6</td>
</tr>
<tr>
<td>Junction 4</td>
<td>Total area 1-6</td>
<td>5.99</td>
<td>----</td>
</tr>
</tbody>
</table>
Table 4. Annual Maximum Peak Streamflow in cubic feet per second at USGS gages 162385000 and 1640500, 1915-1983, for years with peaks recorded on the same date and greater than 500 ft³/s, Waili and Waiakeakua Streams, Oahu, Hawaii

<table>
<thead>
<tr>
<th>Date of Peak</th>
<th>162385000 Peak Flow (ft³/s)</th>
<th>16240500 Peak Flow (ft³/s)</th>
<th>Date of Peak</th>
<th>162385000 Peak Flow (ft³/s)</th>
<th>16240500 Peak Flow (ft³/s)</th>
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<td>10/5/1919</td>
<td>379</td>
<td>507</td>
<td>5/14/1963</td>
<td>2140</td>
<td>1910</td>
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<td>1/16/1921</td>
<td>3250</td>
<td>3090</td>
<td>7/24/1964</td>
<td>551</td>
<td>696</td>
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<td>11/18/1930</td>
<td>1860</td>
<td>883</td>
<td>11/14/1965</td>
<td>2010</td>
<td>2110</td>
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<tr>
<td>4/30/1932</td>
<td>2090</td>
<td>805</td>
<td>12/18/1967</td>
<td>956</td>
<td>1670</td>
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<tr>
<td>1/31/1933</td>
<td>1060</td>
<td>427</td>
<td>11/29/1968</td>
<td>456</td>
<td>1280</td>
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<td>3/2/1939</td>
<td>1400</td>
<td>554</td>
<td>4/14/1972</td>
<td>322</td>
<td>632</td>
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<tr>
<td>1/4/1943</td>
<td>1140</td>
<td>503</td>
<td>11/21/1974</td>
<td>917</td>
<td>1080</td>
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<tr>
<td>4/9/1959</td>
<td>514</td>
<td>325</td>
<td>5/7/1981</td>
<td>480</td>
<td>632</td>
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<td>5/12/1960</td>
<td>1270</td>
<td>1380</td>
<td>8/25/1982</td>
<td>660</td>
<td>679</td>
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<td>12/30/1960</td>
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<td>2400</td>
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The HEC-HMS model results generated a higher peak flow at station 16240500 of 1,350 cfs compared to the observed value of 1,100 cfs with a lower discharge values prior to the peak (Table 5, Figure 5). The model peak of 5,150 cfs was much closer to observed peak of 5,050 cfs at Lowrey Avenue Bridge, station 16241500 in Figure 1, Junction 2 in Figure 4, only a 100 cfs difference, but the model estimated higher discharge values prior to the peak (Table 5, Figure 6). The model peak at the Lowrey Avenue Bridge would be 5,320 cfs including discharge draining from Manoa District Park (Figures 1 and 3; Table 5). The USGS slope-area measurement for station 16241500, which was done upstream of the park’s main drain to Manoa Stream, did not includ all park drainage, so the actual discharge at the Lowrey Avenue Bridge was most likely in the range of 5,100 to 5,300 cfs. The HEC-HMS model did not account for the 2,000 cfs that left Manoa Stream at the Woodlawn Drive Bridge. Assuming that the discharge did not leave the stream channel, the HEC-HMS model discharge at Kanewai Field (Figure 1) should be 7,680 cfs (the observed peak of 5,870 cfs plus 2,000 cfs), but only 6,970 cfs was estimated by the model (Table 5). Thus, the model would need improvement to better represent the lower valley characteristics. The model discharge values prior to the peak at Kanewai Field were also higher than the observed values (Figure 6). Both USGS stream gages at Lowrey Avenue and Kanewai Field were damaged during the flood event so the observed discharge data are not complete (Figure 6).
Table 5. Peak Discharge Magnitudes in cubic feet per second determined by HEC-HMS model and observed at gaging stations, Flood of October 30, 2004, Manoa Stream, Oahu, Hawaii

<table>
<thead>
<tr>
<th>Sub-basin</th>
<th>Description</th>
<th>HMS Model Peak</th>
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<th>Observed Peak</th>
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<td></td>
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<td>Time</td>
<td>Discharge</td>
<td>Time</td>
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<td>19:50</td>
<td>1,100</td>
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<tr>
<td>3</td>
<td>Lowrey</td>
<td>2,410</td>
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<td>Junction 2</td>
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<td>Junction 4</td>
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<td>5,870</td>
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Table 6. Design Storm Rainfall Frequency Duration in inches for Manoa Stream, Oahu, Hawaii

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<th>Percent chance exceedance</th>
<th>Recurrence Interval Year</th>
<th>Duration 5-min</th>
<th>15-min</th>
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<th>2-hour</th>
<th>3-hour</th>
<th>6-hour</th>
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<td>0.45</td>
<td>0.92</td>
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<td>6.85</td>
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<tr>
<td>10</td>
<td>10</td>
<td>0.73</td>
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<td>2.78</td>
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<td>0.87</td>
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<td>10.65</td>
<td>13.30</td>
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<td>6.95</td>
<td>9.70</td>
<td>12.70</td>
<td>15.85</td>
</tr>
</tbody>
</table>
Explanation
--- Observed Rainfall or Streamflow
--- HMS Model Result Streamflow

Figure 5. Observed Rainfall in inches and Observed and Modeled Streamflow in cubic feet per second at Waiakeakua Stream (USGS gage 16240500) for the October 30, 2004 Flood Event
Figure 6. Observed and Modeled Streamflow in cubic feet per second at USGS Gages on Manoa Stream, Flood of October 30, 2004

Manoa Stream at Lowrey Avenue (USGS Gage 16241500)

Explanation:  —— Observed Flow (Missing data at both gages at or about the time of the peak streamflow)
               —— Modeled Flow

Manoa Stream at Kanewai Field (USGS Gage 16242500)
The calibrated model was used with rainfall frequency duration data determined from the rainfall frequency maps and graphical methods presented in Giambelluca and others (1984). These values are presented in Table 6. Data were not adjusted for areal distribution due to the small drainage area size. This source only presents rainfall frequencies from 2 to 100 years (50% to 1% chance exceedance probabilities). This data was used to determine peak flow magnitudes of the 10, 4, 2, and 1 percent chance floods (10-, 25-, 50-, and 100-year floods). Stream flow values at Manoa Stream at Lowrey Avenue Bridge (drainage area of about 4 square miles) and at Kanewai Field (drainage area of about 6 square miles) are compared to the values used in the Flood Insurance Study (FIS) for Manoa Stream (Federal Emergency Management Agency (FEMA, 2000) and the City and County Storm Drainage Standards Plate 6 (City and County of Honolulu, 2000) in Tables 7 and 8. Model results show that the October 30, 2004 flood event was approximately equivalent to a 4 percent or 25-year flood event. Also the hydrologic model determined lower discharge values than those used in the FIS study (Tables 7 and 8).

**Table 7. Comparison of Discharge Frequency Magnitudes in cubic feet per second for Manoa Stream at Lowrey Avenue Bridge, Oahu, Hawaii**

<table>
<thead>
<tr>
<th>Percent Chance Exceedance</th>
<th>Event Year</th>
<th>HEC-HMS</th>
<th>Flood Insurance Study</th>
<th>City &amp; County Plate 6 standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10</td>
<td>4,100</td>
<td>5,600</td>
<td>-----</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>5,200</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>6,000</td>
<td>8,800</td>
<td>-----</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>6,800</td>
<td>10,000</td>
<td>8,000</td>
</tr>
<tr>
<td>0.2</td>
<td>500</td>
<td>-----</td>
<td>12,600</td>
<td>-----</td>
</tr>
</tbody>
</table>

**Table 8. Comparison of Discharge Frequency Magnitudes in cubic feet per second for Manoa Stream at Kanewai Field, Oahu, Hawaii**

<table>
<thead>
<tr>
<th>Percent Chance Exceedance</th>
<th>Event Year</th>
<th>HEC-HMS</th>
<th>Flood Insurance Study</th>
<th>City &amp; County Plate 6 standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10</td>
<td>6,200</td>
<td>7,200</td>
<td>-----</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>7,800</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>9,000</td>
<td>11,400</td>
<td>-----</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>10,200</td>
<td>13,200</td>
<td>12,000</td>
</tr>
<tr>
<td>0.2</td>
<td>500</td>
<td>-----</td>
<td>17,000</td>
<td>-----</td>
</tr>
</tbody>
</table>
Hydraulic Modeling

The hydraulic model used the USACE program HEC-RAS version 3.1.3 (U.S. Army Corps of Engineers, 2002b) and modeled a reach of Manoa Stream from about 800 ft upstream of the Kahaloa Drive Bridge to about 700 feet downstream of the wooden foot bridge at Kanewai Field. The model geometry used two storage area components connected to the main stream channel by lateral weir structures for the over bank flow areas where flood waters left the stream channel (Figure 7). The steady flow analysis was run as a mixed flow (sub- and super-critical flow computations) condition with 5,050 cfs upstream, 5,200 cfs below the Manoa District Park, 5,490 cfs below East Manoa Road Bridge, and 7,680 cfs at Dole Street Bridge as input discharge data and critical depth was used as the downstream and upstream boundary conditions (Table 9). The 7,680 cfs discharge value was determined by adding the 2,000 cfs peak flow determined to have left the stream at Woodlawn Drive to the observed peak at Kanewai Field which was 5,870 cfs. This was done to allow the HEC-RAS model to determine the capacity of the stream channel near Woodlawn Drive and the amount of water which left the stream.

Figure 7. Hydraulic model schematic diagram, Manoa Stream, Oahu, Hawaii
Table 9. Discharge Magnitudes in cubic feet per second used in HEC-RAS to model the October 30, 2004 Flood of Manoa Stream, Oahu, Hawaii

<table>
<thead>
<tr>
<th>Location</th>
<th>RAS Model Cross-Section</th>
<th>October 30, 2004 Flood Values (approx. the 4% flood)</th>
<th>High Discharge Values (approx. the 2% flood)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kahaloa Bridge/ Start</td>
<td>120+00</td>
<td>5,050</td>
<td>6,050</td>
</tr>
<tr>
<td>Park Drainage</td>
<td>104+87</td>
<td>5,200</td>
<td>6,200</td>
</tr>
<tr>
<td>East Manoa Bridge</td>
<td>94+50</td>
<td>5,490</td>
<td>6,490</td>
</tr>
<tr>
<td>Dole Street Bridge/ End</td>
<td>34+00</td>
<td>7,680</td>
<td>8,680</td>
</tr>
</tbody>
</table>

Topographic data, mostly stream channel cross-sections needed for the hydraulic modeling effort were collected from the USACE, C&C, USGS, and State of Hawaii Department of Land and Natural Resources (DLNR). The majority of the stream channel cross section data was surveyed in 1976 and used in the USACE 1977 flood hazard study which formed the basis of the mapped Manoa-Palolo floodplain used by FEMA in the FIS (M&E Pacific, Inc, 1977). Thus, 75 cross-sections out of a total 116 cross sections available were from the 1976 data. Additional data provided by the C&C included topographic, bridge, channel, and road plans for Kahaloa Drive Bridge (dated 1953 and 1998), Lowrey Avenue Bridge and channel (1952), East Manoa Road Bridge (1949 and 1952), Woodlawn Drive road and bridge (1974) and Manoa District Park (2000 and 2002). Additionally, the C&C surveyed six stream channel cross-sections for this study in June 2005. The USGS stream cross-section data consisted of those cross-sections survey in November 2004 for indirect slope-area measurements of peak discharge at Manoa District Park and Kanewai Field. The DLNR provided stream cross-section data downstream of East Manoa Road Bridge (2000). Where different cross-section data were located very near to each other, the data was either merged into one cross-section or the latest dated data was used. The 1976 data was corrected to correspond to the newer data. Cross-section data was interpolated where needed every 50 feet. A total of 128 cross-sections were interpolated of which only 25 interpolated cross-sections were located upstream of Woodlawn Drive Bridge.

Initial results, without any bridge blockages, indicate that there is not sufficient channel capacity to carry these flows. Channel capacity is defined as the amount of flow contained within the channel banks. Channel and bridge capacity data with no bridge blockages are listed in Table 10. Water surface elevations are shown in Figure 8. Flood waters left the channel at Manoa District Park and the remaining flows did cause some overflow at the bridges by East Manoa Road and Woodlawn Drive, but these amounts are not large. Without blockage, there probably would have been some flood waters directed towards the University of Hawaii campus, about 1,200 to 1,300 cfs (Table 10).
To get about 2,000 cfs to leave the stream channel at Woodlawn Drive Bridge, a blockage, modeled in HEC-RAS as an obstruction, of about 45% was needed (Table 11; Photo 3). Any blockage of about 35 to 50% at this bridge would have sent more than 1,500 cfs of floodwaters down Woodlawn Drive. The no blockage condition at Woodlawn Drive Bridge assumes an opening height of about 8 feet on average with about 2 to 4 feet of bed sediment depending on the measurement location and not the clear 10 foot opening in the 1974 design drawings. Post flood observations also showed that the East Manoa Bridge was blocked by a similar if smaller percentage, about 25% blockage, was used to replicate the flooding event at this bridge (Photo 4). The East Manoa bridge blockage affects the amount of water flooding the right over bank area from East Manoa Road back upstream to Manoa District Park. About 1,300 cfs was determined by the model to have affected the right over bank areas between the park and East Manoa Road. The model can not determine how much of the right over bank flow that flowed to Woodlawn Drive through the Manoa Shopping center parking lot.
Table 10. Comparison of Channel and Bridge Discharge Capacity in cubic feet per second, for October 30, 2004 Flood Magnitude (approximately the 4% exceedance flood) without Bridge Blockage Conditions for Manoa Stream, Oahu, Hawaii.

<table>
<thead>
<tr>
<th></th>
<th>October 30, 2004 conditions with no blockage</th>
<th>1 Flood walls or Levee at Woodlawn only</th>
<th>2 Flood walls or Levee at Lowrey and Woodlawn</th>
<th>3 Channel Drop at Woodlawn</th>
<th>4 Channel Drop and flood walls or levee at Woodlawn</th>
<th>5 Concrete Channel</th>
<th>6 Trapezoidal Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Manoa Bridge blockage percent</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Woodlawn Bridge blockage percent</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Kahaloa Bridge</td>
<td>5,000</td>
<td>5,000</td>
<td>5,000</td>
<td>5,000</td>
<td>5,000</td>
<td>5,000</td>
<td>5,000</td>
</tr>
<tr>
<td>Park at Concrete channel start</td>
<td>4,600</td>
<td>4,600</td>
<td>4,900</td>
<td>4,600</td>
<td>4,600</td>
<td>4,800</td>
<td>4,600</td>
</tr>
<tr>
<td>Lowrey Bridge</td>
<td>4,200</td>
<td>4,300</td>
<td>5,200</td>
<td>4,170</td>
<td>4,200</td>
<td>4,200</td>
<td>4,300</td>
</tr>
<tr>
<td>East Manoa Bridge</td>
<td>3,900</td>
<td>3,900</td>
<td>4,300</td>
<td>3,900</td>
<td>3,900</td>
<td>4,200</td>
<td>4,300</td>
</tr>
<tr>
<td>Woodlawn Bridge</td>
<td>2,800</td>
<td>4,200</td>
<td>5,500</td>
<td>4,200</td>
<td>4,200</td>
<td>4,500</td>
<td>4,500</td>
</tr>
<tr>
<td>Dole Bridge</td>
<td>6,200</td>
<td>6,400</td>
<td>7,700</td>
<td>6,400</td>
<td>6,300</td>
<td>6,600</td>
<td>6,700</td>
</tr>
<tr>
<td>Kaneval Field</td>
<td>4,600</td>
<td>4,700</td>
<td>4,100</td>
<td>4,800</td>
<td>4,800</td>
<td>5,100</td>
<td>5,200</td>
</tr>
<tr>
<td>Lowrey Right Overbank to SA</td>
<td>1,300</td>
<td>1,300</td>
<td>0</td>
<td>1,300</td>
<td>1,300</td>
<td>1,000</td>
<td>900</td>
</tr>
<tr>
<td>Woodlawn-Left Overbank to SA</td>
<td>200</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Woodlawn Right Overbank</td>
<td>1,100</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

(continued on following page)
Table 11. Comparison of Channel and Bridge Discharge Capacity in cubic feet per second, for October 30, 2004 Flood Conditions (approximately the 4% exceedance flood) for Manoa Stream, Oahu, Hawaii.

<table>
<thead>
<tr>
<th></th>
<th>October 30, 2004 Flood Condition</th>
<th>1 Flood walls or Levee at Woodlawn only</th>
<th>2 Flood walls or Levee at Lowrey and Woodlawn</th>
<th>3 Channel Drop at Woodlawn</th>
<th>4 Channel Drop and flood walls or levee at Woodlawn</th>
<th>5 Concrete Channel</th>
<th>6 Trapezoidal Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Manoa Bridge blockage percent</td>
<td>25%</td>
<td>25%</td>
<td>25%</td>
<td>25%</td>
<td>25%</td>
<td>25%</td>
<td>25%</td>
</tr>
<tr>
<td>Woodlawn Bridge blockage percent</td>
<td>45%</td>
<td>45%</td>
<td>45%</td>
<td>45%</td>
<td>45%</td>
<td>45%</td>
<td>45%</td>
</tr>
<tr>
<td>Kahaloa Bridge</td>
<td>5,000</td>
<td>5,000</td>
<td>5,000</td>
<td>5,000</td>
<td>5,000</td>
<td>5,000</td>
<td>5,000</td>
</tr>
<tr>
<td>Park at Concrete channel start</td>
<td>4,600</td>
<td>4,600</td>
<td>4,600</td>
<td>4,700</td>
<td>4,600</td>
<td>4,600</td>
<td>4,600</td>
</tr>
<tr>
<td>Lowrey Bridge</td>
<td>4,300</td>
<td>4,300</td>
<td>5,200</td>
<td>4,300</td>
<td>4,200</td>
<td>4,200</td>
<td>4,300</td>
</tr>
<tr>
<td>East Manoa Bridge</td>
<td>3,300</td>
<td>3,800</td>
<td>4,000</td>
<td>3,800</td>
<td>3,400</td>
<td>4,200</td>
<td>4,300</td>
</tr>
<tr>
<td>Woodlawn Bridge</td>
<td>2,000</td>
<td>4,100</td>
<td>1,700</td>
<td>3,700</td>
<td>4,100</td>
<td>4,400</td>
<td>4,500</td>
</tr>
<tr>
<td>Dole Bridge</td>
<td>5,700</td>
<td>6,300</td>
<td>7,400</td>
<td>5,800</td>
<td>6,300</td>
<td>6,600</td>
<td>6,700</td>
</tr>
<tr>
<td>Kanewai Field</td>
<td>4,300</td>
<td>4,500</td>
<td>4,800</td>
<td>6,000</td>
<td>4,500</td>
<td>5,100</td>
<td>5,200</td>
</tr>
<tr>
<td>Lowrey Right Overbank to SA</td>
<td>1,400</td>
<td>-1,400</td>
<td>0</td>
<td>1,400</td>
<td>1,400</td>
<td>1,000</td>
<td>900</td>
</tr>
<tr>
<td>Woodlawn Left Overbank to SA</td>
<td>600</td>
<td>300</td>
<td>400</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Woodlawn Right Overbank</td>
<td>1,500</td>
<td>0</td>
<td>3,500</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

(continued on following page)

Bridge hydraulic computations used the pressure and weir flow method (U.S. Army Corps of Engineers, 2002c) which computes pressure flow when the flow comes in contact with the low chord of the bridge. The weir flow equations are used when the flow goes over the bridge. In looking at the bridge capacities, without any blockage conditions, listed in Tables 10 and 12, the capacity at Kahaloa Road Bridge, although listed as high as 5,400 cfs (Table 12) is actually only about 4,900 cfs for the water surface to stay completely under the bridge. The higher discharges have water surface elevations up to the front face of the bridge railing, creating a potential pressure flow condition under the bridge. The East Manoa Road Bridge has a capacity of about 3,900 cfs (Tables 10 and 12). Capacity of the Woodlawn Drive Bridge is only about 2,800 cfs (Tables 10 and 12). Any debris blockage at this bridge reduces its capacity to about 2,000 cfs (Tables 11 and 13). According to the 1974 bridge drawings, Woodlawn Drive Bridge was constructed with a capacity of 8,300 cfs if improvements to Manoa Stream were done up and downstream of the bridge. However, the bridge will not be able to pass 8,300 cfs until adequate improvements are done upstream and downstream of the bridge.

| Table 12. Comparison of Channel and Bridge Discharge Capacity in cubic feet per second, for High Discharge Magnitudes (approximately the 2% exceedance flood) without Bridge Blockage Conditions for Manoa Stream, Oahu, Hawaii. |
|---------------------------------------------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| October 30, 2004 channel conditions | 1 Flood walls or Levee at Woodlawn only | 2 Flood walls or Levee at Lowrey and Woodlawn | 3 Channel Drop at Woodlawn | 4 Channel Drop and flood walls or levee at Woodlawn | 5 Concrete Channel | 6 Trapezoidal Channel |
| East Manoa Bridge blockage percent | 0% | 0% | 0% | 0% | 0% | 0% |
| Woodlawn Bridge blockage percent | 0% | 0% | 0% | 0% | 0% | 0% |
| Kahaloa Bridge | 5,400 | 5,400 | 5,400 | 5,400 | 5,400 | 5,400 |
| Park at Concrete channel start | 4,600 | 4,700 | 4,700 | 4,900 | 4,900 | 4,900 |
| Lowrey Bridge | 5,600 | 4,900 | 6,200 | 5,880 | 5,700 | 4,900 |
| East Manoa Bridge | 3,800 | 3,900 | 4,500 | 4,110 | 3,800 | 5,200 |
| Woodlawn Bridge | 2,800 | 4,200 | 2,200 | 4,400 | 4,400 | 5,200 |
| Dole Bridge | 6,200 | 6,400 | 8,000 | 6,560 | 6,800 | 7,500 |
| Kanewai Field | 4,500 | 4,700 | 4,100 | 5,280 | 5,300 | 4,800 |
| Lowrey Right Overbank to SA | 2,100 | 2,300 | 100 | 2,090 | 2,100 | 1,000 |
| Woodlawn Left Overbank to SA | 300 | 0 | 600 | 0 | 0 | 0 |
| Woodlawn Right Overbank | 1,300 | 0 | 3,600 | 0 | 0 | 0 |
The model indicates that the channel capacity of Manoa Stream to be about 4,500 cfs to 5,000 cfs, about a 4 percent chance or 25-year flood (Table 7). The Kahaloa Drive, Lowrey Avenue, and Dole Street bridges can pass these flows but the East Manoa Road and Woodlawn Drive Bridges can only safely pass flows about or less than the 10 percent chance or 10-year flood (Table 7). Any higher discharges will cause the bridges to be overtopped. At Kanewai Field, the model had flow leaving the channel upstream of the footbridge. The footbridge has a small capacity, only in the range of about 1,500 to 2,000 cfs depending on the model run conditions. This footbridge has been removed as of January 2006.

Comparing modeled water surface elevations with USGS observed high water marks shows that the hydraulic model results indicate a water surface elevation that is on the average 1.0 foot higher than the observed flood elevations at Manoa District Park for a peak flow of 5,050 cfs and about 0.7 feet higher on average at Kanewai Field for a computed peak flow of 5,930 cfs, only about 60 cfs higher than observed at this location. The higher than observed water surface elevations in the model are mostly due to the geometry data, which is from 1976 and based in part on 5-foot contour interval topographic maps from 1969 and are not as detailed as that used in the slope-area indirect measurement, the conversion of USGS gage datum to mean sea level.

| Table 13. Comparison of Channel and Bridge Discharge Capacity in cubic feet per second, for High Discharge Magnitude (approximately the 2% exceedance flood) with October 30, 2004 Flood Condition Bridge Blockages for Manoa Stream, Oahu, Hawaii. |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                                 | October 30, 2004 channel conditions | 1 Flood walls or Levee at Woodlawn only | 2 Flood walls or Levee at Lowrey and Woodlawn | 3 Channel Drop at Woodlawn | 4 Channel Drop and flood walls or levee at Woodlawn | 5 Concrete Channel | 6 Trapezoidal Channel |
| East Manoa Bridge blockage percent | 25% | 25% | 25% | 25% | 25% | 25% | 25% |
| Woodlawn Bridge blockage percent | 45% | 45% | 45% | 45% | 45% | 45% | 45% |
| Kahaloa Bridge                  | 5,400 | 5,400 | 5,400 | 5,400 | 5,400 | 5,400 | 5,400 |
| Park at Concrete channel start  | 4,600 | 4,700 | 4,700 | 4,700 | 4,600 | 4,600 | 4,900 |
| Lowrey Bridge                   | 5,700 | 4,700 | 5,400 | 4,800 | 5,700 | 5,700 | 4,600 |
| East Manoa Bridge               | 3,800 | 3,400 | 4,100 | 3,800 | 3,400 | 5,000 | 4,800 |
| Woodlawn Bridge                 | 2,100 | 4,200 | 2,000 | 3,000 | 4,100 | 3,400 | 2,900 |
| Dole Bridge                     | 5,700 | 6,500 | 8,200 | 5,900 | 6,300 | 7,600 | 7,000 |
| Kanewai Field                   | 4,300 | 4,200 | 4,700 | 4,500 | 4,900 | 5,500 | 5,500 |
| Lowrey Right Overbank to SA     | 2,400 | 2,200 | 2,000 | 2,400 | 2,400 | 1,200 | 1,300 |
| Woodlawn Left Overbank to SA    | 600   | 0    | 300  | 400  | 0    | 0    | 300  |
| Woodlawn Right Overbank         | 1,500 | 0    | 4,000 | 800  | 0    | 1,900 | 2,000 |

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datum, and the choice of Manning's n roughness coefficient. Manning's n values used for the stream channel were 0.035 upstream of Manoa District Park and downstream of East Manoa Road Bridge, 0.03 through the park, and 0.02 for the concrete lined channels. The grassy over bank areas at the park and field used 0.025 while the over bank areas by houses used an n value of 0.05 to 0.06. Channel and over bank Manning's n values of 0.035 and 0.06 were used in the Flood Insurance Study (FIS).

**Possible Flood Mitigation Alternatives to Prevent Occurrence**

Possible measures to prevent flood damages from a similar magnitude event were modeled using the HEC-RAS model. Six channel modification measures were modeled. These measures consisted of floodwalls or levees by Woodlawn Drive Bridge and by Manoa District Park to East Manoa Road Bridge, a channel modification to increase capacity at Woodlawn Drive Bridge, and channel modifications between East Manoa Road and Woodlawn Drive. In general, any measure to increase stream and bridge capacity would be effective to reduce flood levels since insufficient channel capacity has been identified previously as a major flooding problem in Manoa Stream (State of Hawaii, 1995; Townscape, Inc. and others, 2003). No alternatives into flooding problems along Manoa Stream upstream of Kahaloa Drive Bridge and downstream of Woodlawn Drive Bridge were studied. No detailed analysis into the drainage, structural, aesthetic, or maintenance issues created by any of these possible flood mitigation alternatives was conducted. The steady flow model could not look at alternatives such as break-a-way fences and flap-gates as these type of structures require an unsteady flow model which was beyond the scope of this study. Also, in-channel debris mitigation measures to catch debris and prevent bridge blockages were not studied in great detail as a proper analysis of these types of structures would also require an unsteady flow model.

The first alternative modeled was a floodwall or levee only by Woodlawn Drive Bridge. A levee is usually an earth embankment while a flood wall is usually a concrete retaining wall. The levee or flood wall would need to be 5 feet high along the left bank from the stream bend 500 feet upstream to Woodlawn Drive Bridge and 5 feet high on the right bank from the bridge to about 100 feet upstream to prevent the over flow from occurring here assuming a 45% blockage (Table 11 and Figure 9). The upstream face of the bridge would need to be modified to match the wall or levee height (Table 11). This situation would create a pressure flow condition and allow the bridge to pass a larger discharge value. The bridge structure would have to be analyzed if it could handle a pressure flow situation. This alternative would increase the Woodlawn Drive Bridge capacity to about 4,200 cfs (Tables 10 and 12). Flood waters would still overflow the stream channel at Manoa District Park and Kanewai Field since this alternative does not address flooding at those locations.
The second alternative modeled was extending and raising the existing concrete channel flood wall from Manoa District Park to East Manoa Road and building a floodwall or levee at Woodlawn Drive (alternative one). To prevent flooding to the right over bank area downstream of Manoa District Park, the current concrete channel wall will need to be raised 3 to 4 feet on average, up to 7 feet in some areas (Figure 9). The extension of the wall would have to cut across the park to an elevation of 172 feet, mean sea level datum. This would not alleviate or cause additional flooding to the left bank areas and the levee or floodwall by Woodlawn Drive Bridge would need to be 7 feet high. With 45% blockage at Woodlawn Drive Bridge and 25% blockage at East Manoa Road Bridge there will still be overflow at the East Manoa Road Bridge due to limited bridge capacity caused by the blockage and the containment of the overflows and the Woodlawn Drive Bridge would also overtop. Without any bridge blockages, this alternative provides the highest stream capacity at Woodlawn Drive Bridge (Table 10).
Larger downstream flows would also cause more flooding at Kanewai Field. The additional discharge that stays in the stream channel would increase the water surface elevation at Kanewai Field by 1 foot from 38 to 39 feet. The top of left bank here is elevation 36 feet. Flow from the drainage ditch through Manoa District Park and backwater from the channel will affect the drainage ditch at the downstream end of the park. A 2 to 3 feet high rock wall along the park boundary for about 350 feet from the stream along the boundary would be needed to prevent any flooding from the park to the residential area here (Figure 9). This drainage ditch was modeled as separate channel using HEC-RAS with cross-sections taken from a topographic map of the park and using the peak discharge of 170 cfs determined by the HEC-HMS model (Table 5).

The second alternative would also need a 4 foot tall extension on the left bank of the concrete channel wall to prevent flooding on the left bank but this would result in more discharge overtopping the East Manoa Road and Woodlawn Drive Bridges. Therefore this alternative in attempting to contain the October 30, 2004 Flood discharge in the channel creates the need for higher floodwalls downstream and interior drainage concerns such walls would impose, so is not a feasible alternative to pursue. If only a 2 to 3 foot high wall is built along the downstream park boundary, the backwater upstream in the park is raised by 0.2 feet and the water surface elevation downstream by Lowrey Avenue is reduce by 0.1 feet indicating a storage effect at the park but overall there is no change in the areas that get flooded using the October 30, 2004 discharge values. Additional topographic data would be needed to better determine if any benefit can be provided by this wall.

The third alternative modeled was a concrete drop structure (dam) upstream of Woodlawn Drive Bridge. The concept behind this alternative is to increase flow capacity at Woodlawn Drive Bridge by only modifying the channel near the bridge. The original bridge drawings (1974) show a channel bottom about 2 to 4 feet lower than the 2005 survey measurements indicated due to bed sediment fill. The 1976 survey and recent measurements of the bridge opening height in 2005 indicate that the gravel fill level under the bridge has been constant. The channel modification would consist of dredging the channel for about 40 feet upstream to about 100 feet downstream of the bridge past the first bend and installing a concrete channel bottom and building a 4 foot tall concrete dam 40 feet upstream to hold back the existing stream bed gravel and provide a drop structure to create a supercritical flow condition (Figure 10) and increase in channel slope. With no bridge blockages, Woodlawn Drive Bridge would be able to pass about 4,200 to 4,400 cfs (Tables 10 and 12). Using the flood condition blockages would reduce the capacity of the Woodlawn Drive Bridge and cause over bank flooding (Tables 11 and 13). This option does not reduce any flooding upstream at Manoa District Park or downstream at Kanewai Field by any significant amount but does allow the Woodlawn Drive Bridge to pass higher flows then alternatives 1 and 2 (Table 12) except when blocked (Tables 11 and 13). More detailed modeling of this alternative would be needed to determine the specific structure design and performance.

The fourth alternative modeled was combining alternatives one and three by creating a drop structure and installing floodwalls by Woodlawn Drive Bridge. This
alternative does not increase the discharge able to pass Woodlawn Drive Bridge with no bridge blockages compared with either the floodwalls or channel drop structure alone (Table 10) but does prevent over bank flooding with bridge blockages (Table 11). With higher discharges and bridge blockages, this alternative also prevents flooding at Woodlawn Drive compared to the drop structure alone (Table 13).

The fifth alternative modeled was a rectangular concrete channel between East Manoa Road Bridge and Woodlawn Drive Bridge. This design used a 52 feet wide, 12 to 14 feet high rectangular channel (Figure 11) with a bottom slope of 0.01 and was modeled from East Manoa Road Bridge to 50 feet downstream of Woodlawn Drive Bridge following the current stream alignment and was proposed as an alternative in State of Hawaii (1995) with an alignment having less stream curvature. This design passes the October 30, 2004 flood flows (Tables 10 and 11) but does not prevent overflow along the right bank between Manoa District Park and Lowrey Avenue and over bank flooding at Kanewai Field. With higher discharge values and 45% blockage at Woodlawn Drive Bridge (Table 13), a flow of about 3,400 cfs will still pass through Woodlawn Drive Bridge but over bank flooding will occur on the right bank unless the channel walls are made taller (Table 13).

The sixth alternative looked at was a trapezoidal channel between East Manoa Road Bridge and Woodlawn Drive Bridge. Two channel sizes were modeled, one with a 30 feet wide bottom and 1.5: 1 side slopes with 0.01 bottom slope and the other 40 feet wide with 1:1 side slopes and 0.01 bottom slope. Both channels were assumed rip-rapped with boulders and modeled with a Manning’s n value of 0.03. The smaller 30 feet wide channel was not able to contain the October 30, 2004 flood flows while the larger 40 feet wide channel provides better stream flow capacity. With a 45% blockage at Woodlawn Drive Bridge, a small levee of 1 to 2 feet would be needed on the left and right banks near the bridge to prevent overflows (Table 11). The 40 feet wide channel design also helps reduce but not prevent the right bank overflow upstream by Manoa District Park to about 1,000 cfs (Table 11). The overall increases in channel and bridge capacities by this option does not differ greatly from the rectangular concrete channel alternative (Tables 10 to 13) and would require more detailed design and study to prevent extremely high velocities from eroding the rip-rap.

The modeled bridge capacities at Woodlawn Drive Bridge for alternatives three to six can be increased through more detailed design with additional data collection. Any modification that can increase the flow velocity through either slope or alignment changes will result in a higher bridge capacity at Woodlawn Drive Bridge. This study did not look into optimizing any of the proposed alternatives due to the limited data available.
Figure 10. Concept drawing of 4 foot high concrete drop structure or dam upstream of Woodlawn Drive Bridge, Manoa Stream, Oahu, Hawaii

Figure 11. Typical Rectangular Channel Section from East Manoa Road to Woodlawn Drive, Manoa Stream, Oahu, Hawaii (From State of Hawaii, 1995)
All of the above alternatives were also tested to see if the increased channel or bridge capacities could handle an increase in discharge, roughly from the current 10 to 25 year flood level of protection to the 50-year level. About 1000 cfs was added to the October 30 values (Table 9) to check the capacities at a higher discharge and with higher blockage amounts. The higher discharges (Table 9) represent about a 2% chance or 50-year flood event (Tables 7 and 8). Higher magnitude floods would still be a significant problem (Tables 12 and 13). Results indicate that none of the alternatives would significantly increase the capacities greater than a 4 percent chance or 25 year flood event capacity. Higher discharges would also cause left over bank flow at Kahaloa Drive Bridge. The alternatives with flood walls or levees fails unless these walls or levees are made taller. The concrete channel alternative would also need to have higher flood walls to provide capacity to carry a larger discharge.

An additional analysis was done to see what effect a debris catching net strung across Manoa Stream at the Manoa District Park would have. As previously mentioned, this model is not capable of accurately modeling the geometry or effect of this debris net other than in a crude way. This net structure was placed about 150 feet upstream from the concrete channel. Figure 12 illustrates how this was modeled. The net structure was treated as narrow 0.1 foot wide bridge with 0.1 foot wide piers every 5 feet for 100 feet extending about 10 feet high above the stream bed. Floating debris was created in the HEC-RAS model to approximate an area reduction in the debris net structure approximately of the same area as those used in the bridge blockage computations. A 40 foot wide bypass channel was created on the right bank which limited the backwater upstream in the park to about 0.2 feet. The effect on the downstream bridge capacities is the same as having no bridge blockages (Table 10). This structure does not increase stream capacity but attempts to prevent debris from blocking any bridges. Given the size of this net structure here at the park it would probably be best to look at debris basins or net structures further upstream on the tributaries of Manoa Stream if debris mitigation measures are pursued.
Base Flood Elevation Determination

Any implementation of a short-term flood mitigation measure would need to meet the City and County of Honolulu requirements to not create any additional flooding in the FEMA FIS defined 100-year flood plain (Figure 3). The FIS 100-year flood elevations are called the Base Flood Elevation (BFE). A hydraulic analysis of the proposed new stream channel conditions is done to determine if such a measure causes a rise in the BFE. This type of analysis is often called a “no-rise” determination. For this analysis, the older (1977) HEC-2 model data used in the FIS study was first inputted into the HEC-RAS program to determine a “new” BFE based on the HEC-RAS output. There are differences in the computation procedures between the programs with those in HEC-RAS, especially in this case at the bridges, being superior (U.S. Army Corps of Engineers, 2002c). As much as possible, except at bridges and in flow computation procedure, the FIS HEC-2 data was replicated exactly in HEC-RAS (Figure 13).

The HEC-2 model used cross-sections every 200 feet except at bridges where cross-sections were added 50 feet up and downstream of each bridge, did not account for stream channel bends, had cross-section data entered from right to left looking downstream except at bridges which went from left to right, and used Manning's n values of 0.035 for the natural channel, 0.02 for the concrete channel section, and 0.06 for the over banks. The HEC-RAS flow computation procedure used the mixed flow option while the FIS BFE was based on supercritical flow only. Results are shown in Table 14. Except for a few cross-sections near Woodlawn Drive, the changes in BFE are not large between the two model BFE but the velocity differences are greater. At Woodlawn Drive Bridge, the HEC-RAS model results in a water surface elevation 1.7 feet higher than the original FIS BFE, upstream of Woodlawn Drive Bridge, the HEC-RAS model results in a water surface elevation 3.0 feet lower than the original FIS BFE (Table 14). The cross-section data at cross-sections S and V (Table 14) were artificially extended vertically in both the original HEC-2 FIS and current HEC-RAS models due to limitations of the original data collection.

For the “no-rise” determination, only alternative 3, the channel drop structure, was modeled. The alternative 3 proposed condition was modeled by changing the HEC-2 channel geometry at the Woodlawn Drive Bridge and the cross-sections immediately up and down stream of the bridge to represent this structure and changing the Manning’s n value to 0.02. Model results show Woodlawn Drive Bridge acting as “dam” creating a backwater condition and allowing all flow to pass under the bridge with no overflow as in the original FIS model. Thus, it shows the Woodlawn Bridge capacity to be 10,600 cfs which appears to be much higher than the design capacity of 8,300 cfs. In comparison to the current HEC-RAS BFE, the “no-rise” water surface elevation is only 0.9 feet higher but 2.6 feet higher than the original FIS BFE (Table 14). Upstream of Woodlawn Drive, the alternative 3 water surface elevation is 3.4 feet higher than the HEC-RAS BFE but only 0.4 feet higher than the original FIS BFE.
The results of the HEC-2 and HEC-RAS comparison and "no-rise" computations raises questions about the original HEC-2 modeling effort and the 1976 data used. Due to the age of the FIS BFE data, no real conclusion can be drawn from this comparison at this time. A new data collection and flood plain mapping effort will allow a better determination of any "no-rise" effect for any of the proposed short term alternatives.

Figure 13. Base Flood Elevation hydraulic model schematic diagram, 1977 Flood Insurance Study data, Manoa Stream, Oahu, Hawaii

(continued on following page)
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\(^1\) In feet upstream of mouth of Manoa-Palolo Drainage Canal at Ala Wai Canal.

\(^2\) In feet upstream of mouth of Manoa Stream at confluence with Palolo Stream.

\(^3\) Cross-section endpoint(s) were extended vertically in water surface elevation computations for FIS and RAS computations.

Values in red italics are significantly different from FIS values.

[FIS, Flood Insurance Study; FHS, Flood Hazard Study; RAS, River Analysis System; BFE, Base Flood Elevation; WSEL, Water Surface Elevation]
Conclusions

Results indicate that Manoa Stream, between Kahaloa Drive and Woodlawn Drive has insufficient capacity to contain the flood waters caused by the October 30, 2004 storm. Flood damage was increased by debris blockage of the East Manoa Road and Woodlawn Drive bridges. Frequency analysis using the HEC-HMS rainfall-runoff model determined the October 30, 2004 flood event to be about a 4 percent chance or 25-year flood event. An analysis of bridge and channel capacities determined that Manoa Stream can safely carry about 4,500 to 5,000 cfs within the banks, but the East Manoa Road and Woodlawn Drive Bridges can only safely pass flows in the range of 2,800 to 3,900 cfs without bridge blockages. Flows in this range have a magnitude less than the 10 percent chance or 10-year flood. Alternatives analyzed included levees or floodwalls along selected portions of the stream channel between Manoa District Park and Woodlawn Drive and creating an artificial channel between East Manoa Road and Woodlawn Drive. Of these alternatives, a levee or floodwall from 3 to 5 feet and up to 7 feet high in some locations would provide the highest channel capacity increase at East Manoa Road Bridge and Woodlawn Drive Bridge and best flood protection to the houses on the right bank between Manoa District Park and East Manoa Road but would not alleviate flooding on the left bank between the park and East Manoa Road. Any levee or floodwall alternative would need to be studied further to mitigate drainage, bridge structure, and aesthetic problems. No alternatives into flooding problems along Manoa Stream downstream of Woodlawn Drive Bridge were studied. No detailed analysis into the drainage, structural, aesthetic, or maintenance issues created by any of these possible flood mitigation alternatives was conducted. No evaluation of the monetary costs or impacts on sedimentation and aquatic life of any of the modeled alternatives were conducted.

The channel drop structure at Woodlawn Drive Bridge has the best potential for increasing the capacity here in the short-term with the least amount of maintenance, aesthetic, bridge structure, and drainage problems to mitigate. Larger discharges on the order of a 2 percent chance or 50-year flood would still cause over bank flooding regardless of the alternative. Flood walls, levees, or artificial channels will need to be taller or wider to carry flows greater than 6,000 cfs. None of the short-term alternatives analyzed will provide protection from a 1 percent chance or 100-year flood event. As a minimum new high resolution topographic data of the Manoa Stream area should be collected. Once collected, such a data set can be used to re-evaluate the FIS 100-year floodplain and study the short-term mitigation channel drop alternative in detail.
List of References

City and County of Honolulu, 2000, Rules Relating to Storm Drainage Standards, Department of Planning and Permitting, City and County of Honolulu, 56p.


