CENTRAL OAHU WATERSHED STUDIES

WAIKELE STREAM
HSPF MODEL DEVELOPMENT

HYDROLOGY AND SEDIMENT CALIBRATION REPORT

Prepared for:

WSP U.S.A.
(formerly Parsons Brinckerhoff, Inc.)
1001 Bishop Street, Suite 2400
Honolulu, HI 96813

On behalf of:

City and County of Honolulu
Department of Environmental Services
Honolulu, HI

September, 2017

NHC Ref. No. 21831

nhc
northwest hydraulic consultants
water resource specialists

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Prepared by:

Northwest Hydraulic Consultants Inc.
Seattle, WA

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AAF	ARMY AIR FIELD (WHEELER)
AFSY	ANNUAL FINE SEDIMENT YIELD
AWC	AVAILABLE WATER CAPACITY
CCH	CITY AND COUNTY OF HONOLULU
C-CAP	NOAA COASTAL CHANGE ANALYSIS PROGRAM
CFS	CUBIC FEET PER SECOND
DOA	STATE OF HAWAII, DEPARTMENT OF AGRICULTURE
DLNR	STATE OF HAWAII, DEPARTMENT OF LAND AND NATURAL RESOURCES
DOLE	DOLE FOOD COMPANY
DOH	STATE OF HAWAII DEPARTMENT OF HEALTH
EIA	EFFECTIVE IMPERVIOUS AREA
ELEV	ELEVATION
DFM-SWQ	CITY AND COUNTY OF HONOLULU DEPT. OF FACILITY MAINTENANCE STORMWATER QUALITY BRANCH, formerly ENVIRONMENTAL SERVICES-ENV
GIS	GEOGRAPHIC INFORMATION SYSTEM
GPM	GALLONS PER MINUTE
HEC-RAS	HYDROLOGIC ENGINEERING CENTER'S RIVER ANALYSIS SYSTEM
HSPF	HYDROLOGIC SIMULATION PROGRAM FORTRAN
K	SATURATED HYDRAULIC CONDUCTIVITY
MGD	MILLION GALLONS PER DAY
NEXRAD	NEXT-GENERATION RADAR
NHC	NORTHWEST HYDRAULIC CONSULTANTS, INC.
NOAA	NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NRCS	NATIONAL RESOURCE CONSERVATION SERVICE
NWS	NOAA NATIONAL WEATHER SERVICE
NWIS	USGS NATIONAL WATER INFORMATION SYSTEM
PRISM	PRISM CLIMATE GROUP AT OREGON STATE UNIVERSITY
SIM.	SIMULATED
SSURGO	NRCS SOIL SURVEY GEOGRAPHIC DATABASE
TIA	TOTAL IMPERVIOUS AREA
TMDL	TOTAL MAXIMUM DAILY LOAD
USACE	U.S. ARMY CORPS OF ENGINEERS
USEPA	U.S. ENVIRONMENTAL PROTECTION AGENCY
USGS	UNITED STATES GEOLOGICAL SURVEY
WARMF	WATERSHED ANALYSIS RISK MANAGEMENT FRAMEWORK
WSP	WSP | PB, formerly PARSONS BRINCKERHOFF, HAWAII
WWTP	WASTEWATER TREATMENT PLANT

1 INTRODUCTION

1.1 Background

The City and County of Honolulu Department of Facility Maintenance Stormwater Quality Branch (DFM-SWQ) is developing programs to maintain and improve the quality of water discharged into Central Oahu Watershed streams. DFM-SWQ engaged WSP, formerly known as Parsons Brinkerhoff (PB), and Northwest Hydraulic Consultants (NHC) to develop a model for the Waikele watershed as a pilot study for potential use on other Oahu watersheds. The model will be used to prepare planning level analyses for management practices and to assist with future Total Maximum Daily Load (TMDL) regulations. The key water quality component currently considered in the model is sediment load.

Following a review of available data and DFM-SWQ's modeling needs, PB and NHC (2010) piloted an application of the WARMF watershed model to the Waikele watershed. That model was calibrated to measured sediment loads at United States Geological Survey (USGS) gages based on available information about the relative contribution of land and stream-based sediment sources and the distribution of sediment sources within the watershed. Subsequent studies by the USGS (Izuka, 2012) indicated that the contribution of stream-based sources may be less, and the land-based contribution may be more than adopted for the pilot model. In order to resolve this issue, DFM-SWQ funded a geomorphic study of the watershed with the broad goal of understanding the production and delivery of sediment from different erosion processes or sources, the distribution of these processes or sources over the watershed, and the volumes they contribute to streams. The understanding gained from the geomorphic study was used to help inform calibration of the watershed model sediment routines. The geomorphic assessment (NHC, 2016) is included as Appendix A of this report.

Since the time PB and NHC (2010) was drafted and the geomorphic study was initiated by NHC in 2011, DFM-SWQ had decided to use an Hydrologic Simulation Program – FORTRAN (HSPF) model of Waikele Stream developed by the State of Hawaii Department of Health (DOH) instead of WARMF. This decision was based on two factors: Firstly, in 2010, DOH had begun development of an HSPF model of Waikele Stream with the intention of developing a TMDL for the basin (DOH and NHC, 2010). Secondly, NHC had found limitations with WARMF in the context of Oahu hydrology and recommended that HSPF would be more functional for both DFM-SWQ and DOH's purposes. The process and data requirements for calibrating HSPF and WARMF are similar, so the application of the information gained from the geomorphic assessment would be applied in a similar manner regardless of which watershed model was used. In 2014, DFM-SWQ re-initiated calibration of the HSPF model to sediment data, but deferred calibration of HSPF nutrient data to a later date.

In 2015, the Environmental Protection Agency (USEPA) and DOH initiated a Waikele Stream TMDL working group to advance development the Waikele Stream TMDL. At that time, NHC was finishing calibration of the HSPF model sediment routines to the USGS data and the findings of NHC's geomorphic assessment for DFM-SWQ. The TMDL working group agreed that the HSPF model is the best tool available for development of a sediment TMDL and also that it should be expanded to include phosphorus and nitrogen routines in order for the TMDL to include nutrients as well. For that to occur, the HSPF model's nutrient routines need to be calibrated, which was funded by USEPA and DOH in a contract to Tetra Tech and NHC. Calibration of the model's nutrient routines and development of the TMDL will be documented separately.

This report is limited to documentation of the HSPF model's development and calibration of the model's hydrology and suspended sediment routines. With the exception of calibration to US Army data (which was not made available until early 2016), all of the work in this report was conducted and funded in order to support DFM-SWQ's watershed planning needs. Addition of the US Army's data to the study required further model updates and calibration for the Upper Waikele Stream that was not included in NHC's contract with DFM-SWQ; this work was initiated in early 2017 with funding provided by the USEPA and DOH.

1.2 Brief Overview of HSPF Watershed Model Platform

Hydrologic and water quality modeling was performed using HSPF version 12.4 (Bicknell, 2014), currently maintained by the U.S. Environmental Protection Agency (USEPA). HSPF is a sophisticated computer modeling program that simulates the hydrologic—and associated water quality processes—on pervious and impervious land surfaces, and in streams and well-mixed impoundments, for extended periods of time. The following overview of HSPF is adapted and excerpted from the USGS web site: http://water.usgs.gov/cgi-bin/man_wrdapp?hspf

HSPF uses continuous rainfall and other meteorologic records to compute streamflow hydrographs and pollutographs. HSPF simulates interception soil moisture, surface runoff, interflow, base flow, snowpack depth and water content, snowmelt, evapotranspiration, ground-water recharge, dissolved oxygen, biochemical oxygen demand BOD), temperature, pesticides, conservatives, fecal coliforms, sediment detachment and transport, sediment routing by particle size, channel routing, reservoir routing, constituent routing, pH, ammonia, nitrite-nitrate, organic nitrogen, orthophosphate, organic phosphorus, phytoplankton, and zooplankton. Program can simulate one or many pervious or impervious unit areas discharging to one or many river reaches or reservoirs. Frequency-duration analysis can be done for any time-series. Any time step from 1 minute to 1 day that divides equally into 1 day can be used. Any period from a few minutes to hundreds of years may be simulated. HSPF is generally used to assess the effects of land-use change, reservoir operations, point or nonpoint source treatment alternatives, flow diversions, etc. Programs, available separately, support data preprocessing and postprocessing for statistical and graphical analysis of data saved to the Watershed Data Management (WDM) file.

METHOD
The model contains hundreds of process algorithms developed from theory, laboratory experiments, and empirical relations from instrumented watersheds. Soil moisture accounting is based on a strict mass balance. Runoff and associate pollutants are routed from land units to streams and other waterbodies in three components using linear and non-linear reservoir methods. Routing of flows in stream segments, reservoirs, and lakes is based on the equation of continuity and discharge as a function of segment storage.

DATA REQUIREMENTS
Meteorologic records of precipitation and estimates of potential evapotranspiration are required for watershed simulation. Air temperature, dewpoint temperature, wind, and solar radiation are required for snowmelt. Air temperature, wind, solar radiation, humidity, cloud cover, tillage practices, point sources, and (or) pesticide applications may be required for water quality simulation. Physical measurements and related parameters are required to describe the land area, channels, and reservoirs.

HISTORY AND APPLICATIONS
The model was developed in the early 1960's as the Stanford Watershed Model. In the 1970's, water quality processes were added. Development of a Fortran version incorporating several related models using software engineering design and development concepts was funded by the Athens, Ga., Research Lab of EPA in the late 1970's. In the 1980's, preprocessing and postprocessing software, algorithm enhancements, and use of the USGS WDM system were developed jointly by the USGS and EPA. The current release is Version [12.4]. An interactive version (see HSPEXP) was developed by the USGS in the 1990's.

There have been hundreds of applications of HSPF all over the world. The largest application is the 62,000 square mile tributary area to the Chesapeake Bay. The smallest application has been experimental plots of a few acres near Watkinsville, Ga. The most significant applications within the USGS have been in the Seattle area, Chicago area, Patuxent River, Md., Truckee-Carson Basins, Nev., and watersheds in Pennsylvania.

1.3 Prior Studies

There are a number of different studies that have looked at flooding, sediment, and other water quality aspects of the Waikele Stream Watershed in recent years, and all have contributed toward the HSPF model and pool of knowledge summarized by this study. Those most relevant are summarized as follows:

- **Geomorphic Assessment of Waikele Watershed – Sediment Budget (NHC, 2016).** As discussed previously in Section 1.1, this report (included as Appendix A) was drafted by NHC's geomorphologists as a predecessor to the current HSPF modeling work to characterize sediment sources and establish targets for the HSPF model calibration.

  An earlier memorandum (NHC, 2011) reviewed the studies, publications, and databases that describe erosion, transport, and deposition of sediment in the Waikele Watershed—or nearby on Oahu—and concluded that the existing information was adequate to develop a rapid sediment budget for the Waikele Watershed. The memorandum also identified important data gaps and suggested methods or approaches to fill these gaps. Most of the content from this earlier memorandum was incorporated into the NHC (2016) report.

- **Review of Izuka, S. 2012. Sources of Suspended Sediment in the Waikele Watershed, Oahu, Hawaii. USGS Scientific Investigations Report 2012-5085. 28p. (NHC, 2014).** This review memorandum identified new information about sediment sources in the watershed that should be used to update a 2011 draft of NHC's geomorphic assessment. The outcomes of this review are reflected in the final version of the geomorphic assessment (NHC, 2016).

- **Izuka, S. 2012. Sources of Suspended Sediment in the Waikele Watershed, Oahu, Hawaii. USGS Scientific Investigations Report 2012-5085. 28p. (Izuka, 2012).** This USGS report provided a summary of the USGS's 2007-2010 sediment monitoring program and gives a summary of sediment sources in the watershed.

- **Waikele Stream Monitoring Recommendation Map (NHC, 2011).** This memorandum provided recommendations to DFM-SWQ for additional hydrometric monitoring in the Waikele Stream Watershed.

- **Central Oahu Watershed Study, Phase 2 – Part B (PB and NHC, Draft 2010).** This report documented a pilot application of the WARMF watershed model to Waikele Stream. The model application, completed before the USGS sediment monitoring program results were released, identified a significant amount of uncertainty in the relative amounts of channel derived vs. landscape derived sediment sources in the watershed. NHC recommended DFM-SWQ conduct a geomorphic assessment to confirm the relative source contributions and revisit the model calibration.

- **Central Oahu Watershed Study, Phase 2 – Part A (PB and NHC, 2008).** This report documented a review of available data and recommendations of watershed models for use by DFM-SWQ. The top two models included WAMRF and HSPF. WARMF was selected for pilot application to Waikele Stream.

- **Central Oahu Watershed Study Final Report, Phase 1 (Oceanit, Townscape Inc., and Eugene Dashiell, 2007)**. The Phase 1 Study Report identified water resource problems and potential solutions for all of the streams that drain to Pearl Harbor (nine watersheds total), as well as the Ewa Plain (Makaiwa and Kaloi). The Phase 1 Study Report further recommended the development of a watershed model that could simulate hydrologic conditions and determine sediment loadings within the Central Oahu watersheds. Prepared for Honolulu Board of Water Supply, U.S. Army Corps of Engineers, and City and County of Honolulu DFM-SWQ.

Other literature resources relating to sediment transport in the watershed are discussed in the sediment budget document (NHC, 2016) included in Appendix A.

1.4 Definitions of Terms

Some of the terms that are commonly used in this report are defined below:

- Suspended sediment concentration (SSC): The dry weight of sediment in a given volume of water, expressed as milligrams/liter (mg/L). USGS concentrations represent the average over the stream cross section rather than that of an individual grab sample.

- Suspended sediment discharge: The weight of suspended sediment carried past a point per unit time, as calculated from the suspended sediment concentration and the water discharge. The USGS publishes daily and annual discharges in tons/day. The weight of sediment transported past a point in a year is the annual discharge multiplied by 365 and is expressed in tons or tons/year.

- Suspended sediment load: The weight of sediment carried past a point over some time period. The load is expressed in tons.

- Fine sediment discharge or load: A portion of the suspended sediment discharge or load that consists of silt and clay (particle diameters less than 62.5 microns). This portion varies with flow, but silt and clay compose most of the suspended load in Hawaii.

- Sediment yield: The total weight of sediment delivered to a point in the watershed averaged over a number of years, and often expressed per unit area of watershed as tons per mi^2.

1.4.1 Fluvial Sediment Transport

Figure 1 illustrates the nomenclature adopted for sediment transport and bed sediment layers. The total sediment load carried by a stream can be divided into suspended and bed transport modes (left side of Figure 1). The suspended load consists of clay and silt-sized sediment maintained in suspension by turbulence, with sand suspended during high flows when turbulence is greatest. Bed load consists of the coarser particles transported along the bed by rolling, sliding, or saltating. The boundary between the size of particles moved in suspension or as bed load is not precise and varies with the flow strength; generally, the greater the flow, the coarser the sediment that can be suspended by turbulence.

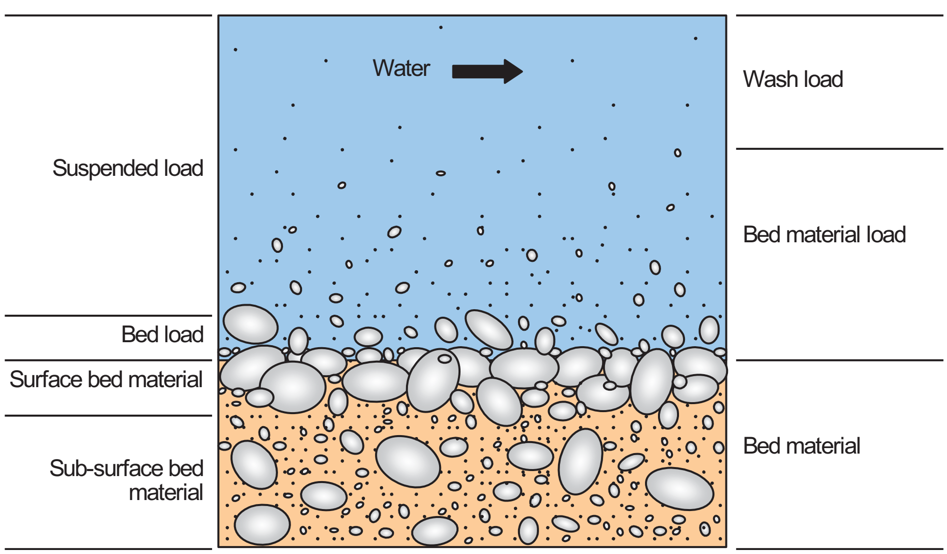


Figure 1: Sediment Transport and Bed Material Definitions

The total sediment load can also be divided by its presence in the streambed into bed material and wash loads (right side of Figure 1). Particles that are found in significant quantities in the bed and are exchanged with the bed load during transport are part of the bed material load. The wash load consists of fine sediments (usually silt and clay) that are continuously maintained in suspension and, thus, are not found in the bed in significant quantities. The wash load transport rate is determined by supply and may be poorly correlated with the rate of water discharge.

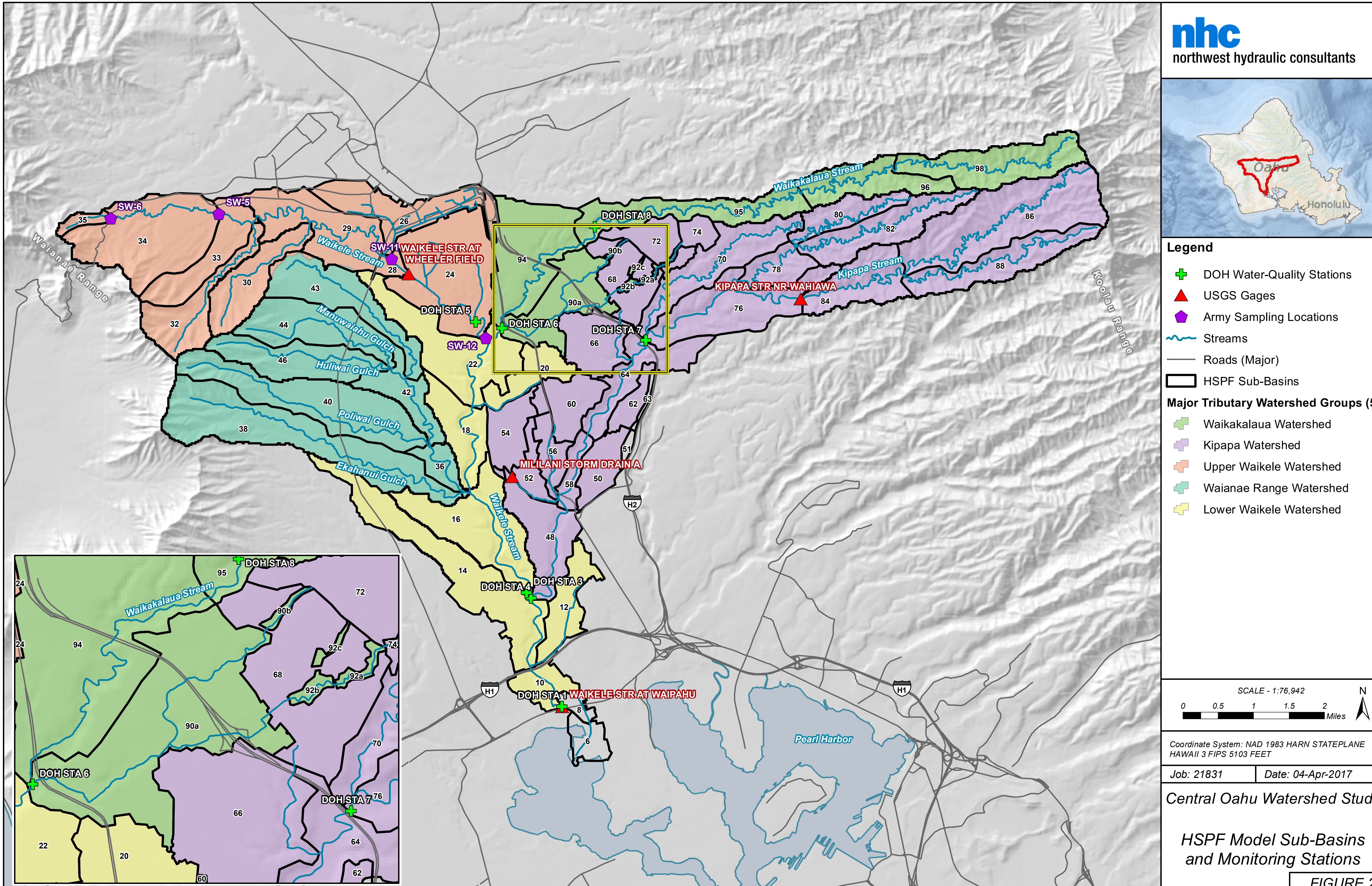
Bed load transport occurs when the stresses or velocities imposed by the flow exceed the critical stress or velocity for the threshold of movement for surface bed material. The coarse beds observed in streams of the mid and upper Waikele Watershed typically have a surface armor layer that is void of fine sediments (silt, clay and fine sand); fine sediments are stored in the sub-surface bed material (Figure 1). Erosion and transport of the fine sediments in the sub-surface layer only occur after the coarser surface bed materials are mobilized. This occurs infrequently in most coarse bed streams and, as a result, the bed only infrequently contributes to the wash load or suspended size sediments. The volume of silt and clay stored in alluvial sub-surface bed material is typically only one to two percent of the total weight, although the total wash load may be increased by attrition of larger particles when they are transported.

Sediment transport, particularly as bed load, can result in collisions and abrasion that produces finer sediments by physical breakdown of coarser ones (referred to as ‘attrition’). The volume of fine sediment produced by this process depends on the geology or nature of the sediments, and on the distances that they travel. Hill *et al* (1998) identified this process as an important contributor to the fine sediment budget in North Halawa Stream because deep chemical weathering results in coarse clasts—composed of secondary minerals—that break down rapidly. This process can be incorporated in the sediment budget by increasing the observed fine sediment content of the erosion source material to account for breakdown of the coarse fraction, or by specifically calculating attrition as a component of sediment transport.

1.5 Waikele Stream Watershed

Waikele Stream flows south across the Schofield and Oahu plains into the West Loch of Pearl Harbor (State Stream Identification No 3-4-10). The upper watershed extends into the eastern slopes of Waianae Range, and also into the leeward or western slopes of Koolau Range. The main tributaries from Koolau Range are the Kipapa and Waikakalaua Streams; from the Waianae Range they are the North and South Waikele Stream and Huliwai, Poliwai, Manuwaiahu, and Ekahanui Gulches. The total watershed area of Waikele Stream to the mouth is 48.4 sq. mi (PB and NHC, 2010). For this study, the Waikele Watershed is defined as the area above the Waikele Stream at Waipahu USGS gage (16213000). This gage is on the westbound Farrington Highway Bridge, about 0.6 miles upstream of Pearl Harbor and has a watershed area of 46.1 sq mi. This watershed area, shown in Figure 2, is larger than that quoted by the USGS and was revised based on an improved delineation of stormwater drainage boundaries.

Much of that content from the following two sub-sections (Physiography 1.5.1 and Stream Descriptions 1.5.2) has been copied from Chapters 2.4 and 2.6 of the Waikele Stream Geomorphic Assessment (NHC, 2016), which are included as part of Appendix A. The reader is referred to Appendix A for additional details about the geomorphic properties of Waikele Stream.


nhc
northwest hydraulic consultants
Oahu
Honolulu
Legend
DOH Water-Quality Stations
USGS Gages
Army Sampling Locations
Streams
Roads (Major)
HSPF Sub-Basins
Major Tributary Watershed Groups (5)
Waikakalaua Watershed
Kipapa Watershed
Upper Waikele Watershed
Waianae Range Watershed
Lower Waikele Watershed
SCALE - 1:76,942
0 0.5 1 1.5 2 Miles
N
Coordinate System: NAD 1983 HARN STATEPLANE HAWAII 3 FIPS 5103 FEET
Job: 21831
Date: 04-Apr-2017
Central Oahu Watershed Study
HSPF Model Sub-Basins and Monitoring Stations
FIGURE 2
Waianae Range
Koolau Range
Waikakalaua Stream
Waikele Stream
Kipapa Stream
Manuwaiahu Gulch
Huliwai Gulch
Poliwai Gulch
Ekahanui Gulch
Pearl Harbor
SW-6
SW-5
SW-11
SW-12
WAIKELE STR AT WHEELER FIELD
KIPAPA STR NR WAHIAWA
MILILANI STORM DRAIN A
WAIKELE STR AT WAIPAHU
DOH STA 1
DOH STA 3
DOH STA 4
DOH STA 5
DOH STA 6
DOH STA 7
DOH STA 8
H1
H2

1.5.1 Physiography

The Waikele Watershed includes parts of the western (leeward) slopes of the Koolau Ranges, the Schofield and Oahu Plains, and the eastern (windward) slopes of the Waianae Ranges. The Koolau Range and the Schofield and Oahu Plains are formed in Koolau Volcano basalts; the Waianae Range in the older Waianae Volcano basalts (Sherrod et al, 2007). Other geologic features include older alluvial and alluvial fan deposits along the eastern side of the Waianae Range that include much of the active agricultural and incised valleys (referred to as "gulches") along Waikele and Kipapa Stream within the Oahu Plain that are partly filled with recent and older alluvium.

About 60 percent of the watershed has slopes of less than 20 percent (11 degrees) and these are primarily in the Schofield and Oahu Plains. Steep slopes on the plains lie along the walls of the incised Waikele and Kipapa stream valleys. The steepest slopes are in the subwatersheds that extend to the crest of the Koolau Range and, to a lesser extent, the Waianae Range. Average slopes in these watersheds are around 50 percent (26 degrees) and up to one-fifth of the area in these subwatersheds lies in the steepest slope class (>80 percent or 40 degrees) where landslides commonly occur.

The steep areas of the Koolau and Waianae Ranges are described as "rough mountainous land" and "tropohumults-dystrandets," and little information is available on their characteristics. Soils on the Schofield and Oahu Plains are well described and consist primarily of silty clay Inceptisols, Oxisols, and Utisols.

Additional details regarding the application of soil classifications to the HSPF model are provided in Section 3.1.3.

1.5.2 Stream Descriptions

The following sections provide a brief description of the major tributary watersheds. Long profiles and summaries of stream types by subwatershed are included in Appendix A. More detailed descriptions are provided in PB and NHC (2010) and Oceanit, Townscape, Inc. and Eugene Dashiell (2007).

Waikakalaua Tributary Watershed

The headwaters of Waikakalaua Stream drain the forested, deeply-dissected, eastern slopes of the Koolau Range near Puukaaumakua Peak. The upper watershed is conservation land and is now undisturbed by human activity. Feral pig wallows have been observed near the stream. Annual precipitation in the upper part of this tributary is the greatest in the Waikele Watershed (>200 in/yr). Stream flow is perennial in the upper watershed.

The stream has a very sinuous course in its upper watershed, formed primarily in bedrock, with narrow floodplains, steep banks, and very coarse bed material (Photo 1, left). Below elevations of about 600 feet, Waikakalaua Stream flows through a narrow, steep-sided gulch or valley that has been mostly filled with housing. Sections of the stream have been moved or relocated to accommodate development. The stream appears to be incised, with steep banks, bank protection, and saprolite or bedrock exposed in the bed (Photo 1, right). The general appearance during field inspections was of recent bed lowering and bank erosion.

Waikakalaua Stream joins upper Waikele Stream within the Wheeler Air Base at an elevation of about 540 feet. There is little sediment storage at the junction in either stream.

Photo 1: (left) Tortuous channel of Waikakalaua Stream incised in bedrock; and (right) View of bed material (saprolite) in Waikakalaua Stream in Mililani Park.

Kipapa Tributary Watershed

The headwaters of the North and South forks of Kipapa Watershed are just south of Waikakalaua Watershed (Photo 2, left). The upper watershed is conservation land and is now undisturbed by human activity but plentiful landslides have occurred (Photo 2, right). Feral pig wallows have been observed near the stream and on the valley walls. Annual precipitation in the upper part of this tributary is greater than 200 in/yr.

Photo 2: (left) Headwall of upper Kipapa Stream showing debris slides; and (right) View of debris slide/bedrock exposure in upper Kipapa Watershed.

Similar to Waikakalaua Stream, the Kipapa forks have a very sinuous course, formed primarily in bedrock, with narrow floodplains, steep banks, and very coarse bed material. The individual stream channels are considerably smaller than Waikakalaua Stream. Photo 3 (left) provides a ground-level photo of Kipapa Stream upstream of the USGS gage. Photo 3 (right) provides a view up the valley towards the Koolau Range.


Photo 3: (left) View upstream on Kipapa Stream, from USGS gage; and (right) View up the Kipapa Valley towards the Koolau Range.

Downstream of the USGS stream gage and junction with the North Fork, Kipapa Stream flows through a prominent gulch or narrow valley incised into the Oahu Plain (Photo 4, left). The gulch has a moderately wide bottom and steep side slopes, and the stream is less sinuous than further upstream. Land use consists of urban/residential along the western side of the gulch, agriculture on the eastern side (Photo 4, right), conservation in the uplands, and forest along the stream banks and tributaries. Patches of crops grow on the bottom of the gulch, primarily banana and papaya.


Photo 4: (left) View of Kipapa Gulch and Oahu Plain, looking downstream towards Pearl Harbor; and (right) View across Kipapa Gulch to Mililani Town; agricultural fields and native surfaced road in foreground.

The bottom of the Kipapa Gulch narrows as it approaches the confluence with Waikele Stream to about 1,000 to 1,500 feet. Large boulders are observed in the stream bed and the banks are lined with trees. The valley bottom is a military reservation. An access road runs along each side of the stream, with a bridge crossing about two miles upstream of the confluence.

Upper Waikele Tributary Watershed

The headwaters of the upper Waikele Watershed (above the Waikakalaua confluence) are in the Waianae Range. Maximum elevations are about 2,900 feet in the North fork and 2,300 feet in the South fork on either side of Kolekole Pass. The upper forested slopes are deeply dissected and mostly forested, but with patches of exposed, eroding bedrock. Part of the northern upland area is used by the US Army for training.

The lower part of the tributary watershed is adjacent to the Schofield Barracks and Wheeler Air Field. Military facilities are primarily on the north side of the stream. The lower 5,000 feet of the stream, adjacent to Wheeler Air Field, have been straightened. In this reach, the channel is well-incised with steep banks and saprolite exposed in the stream bed near the USGS gage (Photo 5, left). Photo 5 (right) shows the mouth at the junction with Waikakalaua Stream and the incision into hard bed materials.

Photo 5: (left) View downstream on upper Waikele Stream (towards culvert) in vicinity of USGS gage; and (right) View of Upper Waikele Stream from bridge on Wheeler Field at junction with Waikakalaua Stream.

Waianae Range Tributary Watershed

This tributary watershed includes Huliwai, Poliwai, Manuwaiahu, and Ekahanui Gulches. The upper parts of the watershed are in the Waianae Range with maximum elevations of 2,400 to 3,100 feet. The upper watershed is deeply dissected but is maintained as undisturbed conservation land. The lower parts of the tributary watersheds, on the fans formed below the Waianae Range, are prime agricultural land (Photo 6, left and right).


Photo 6: (left) View of agricultural fields, field roads on west side of Waikele Stream; and (right) View to north (Waianae Range in left background) of agricultural fields on west side of Waikele Stream.

Lower Waikele Watershed

The lower Waikele Watershed is the part of the watershed that drains to Waikele Stream downstream of the confluence of upper Waikele and Waikakalaua Streams near Wheeler Air Field—exclusive of the Waianae Range and Kipapa Tributary watersheds. The broad gulch of Waikele Stream is incised well below the Schofield and Oahu plains. The gulch is incised up to 300 feet and the bottom is about 1,500 feet wide. Much of the valley bottom is military reservation and is partly covered with access roads. The Navy's Lualualei Magazine (Waikele Branch), which was excavated into the steep, bedrock valley walls, is now used for public storage. Downstream of the upper Farrington Highway crossing, Waikele Stream flows in a concrete-lined channel.

Waikele Stream has a wide, shallow boulder-cobble bed through much of this tributary watershed. Banks are lined with tall grass and trees (see Photo 7, left and right).

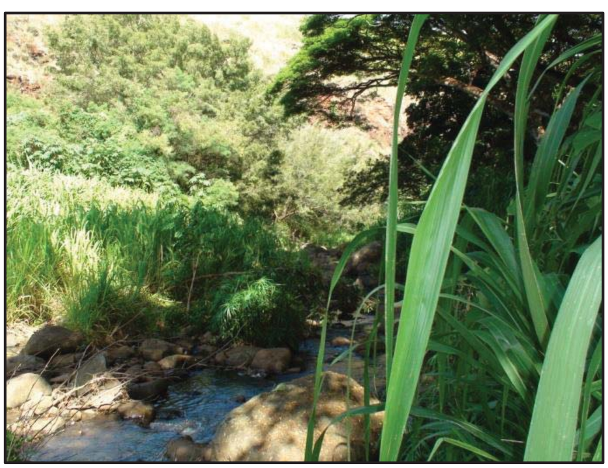



Photo 7: (left, taken August 2, 2011) Waikele Stream downstream of Huliwai confluence; and (right, taken August 3, 2011) looking upstream at Waipahu Street.

Additional watershed photos are included in Appendix A.

1.5.1 Fine Sediment Erosion Source Budget for Waikele Stream Watershed

The sediment budget completed by NHC (2016) summarized the annual fine sediment yield (AFSY) from the significant erosion processes in the Waikele Stream Watershed. A summary of the sediment budget provided by that report is provided as Table 1, and the full report is included as Appendix A. The table divides the fine sediment yield calculated for the five main tributaries into conservation land, urban sources, and stream erosion. The dominant source of fine sediments in the overall Waikele Watershed is surface erosion from human-modified terrain, and most of these sediments are derived from erosion in agricultural fields. The human-modified terrain provides about 64 percent of the AFSY; natural hillslope process provide about 19 percent; and stream bank erosion throughout the watershed provides the remaining 17 percent. The individual dominant erosion processes are surface erosion from agriculture, debris slides and flows, unpaved roads, and stream bank erosion. These four processes contribute over 90 percent of the annual fine sediment yield. The other seven erosion processes provide the remaining AFSY and are relatively insignificant contributors in the Waikele Watershed.

Table 1: Fine Sediment Erosion Source Budget for the Waikele Stream Watershed

Erosion Process	AFSY by Subbasin (tons)					AFSY Waikele Watershed (tons)
	Waikakalaua	Kipapa	Upper Waikele	Waianae Range	Lower Waikele	
Conservation Lands						
Debris Slides/Flows	1,400	2,600	220	170	0	4,400
Saprolite Landslides	80	170	0	0	0	250
Soil Creep	20	80	20	40	10	170
Landslide Scars	240	420	40	20	0	730
Feral Animals	110	170	0	0	0	280
Subtotal						5,800
Urban Lands	40	90	60	10	50	250
Military Training Sheet Wash	0	0	300	0	0	300
Agriculture Sheet Wash	20	2,300	2,900	6,500	4,700	16,400
Un-Paved Roads Sheet Wash	170	530	560	340	520	2,100
Paved Roads Sheet Wash	0	50	50	0	0	100
Subtotal						19,200
Stream Erosion						
All Stream Types	560	1,960	750	820	1,010	5,100
TOTAL ANNUAL LOAD (tons)	*2,600*	*8,400*	*4,900*	*7,900*	*6,300*	*30,100*[1]
TOTAL ANNUAL YIELD (tons/day/mi²)	*1.23*	*1.48*	*1.44*	*2.58*	*2.50*	*1.79*
[1] MEASURED AFSY AT WAIKELE GAGE (1973 to 2010)						

2 PRECIPITATION AND OTHER METEOROLOGICAL DATA

The Waikele Stream HSPF model is divided into six precipitation zones with a unique time-series of precipitation applied to each zone (see Table 2 and Figure 3). The complete set of rain gages utilized either as a primary rain gage, or for filling of primary rain gages, is provide as Table 3. Based on previous modeling experience with watersheds on Oahu and other Hawaiian islands, it has been apparent that existing rain gage networks are typically not of sufficient density to reliably represent the spatial variability of individual storms, or to allow reliable calibration to gaged storm hydrographs. In some cases, high flow would be observed at a discharge gage but there would be little or no precipitation recorded at a rain gage nearby the flow monitoring site. To solve this problem, Next Generation Weather Radar (NEXRAD) Level III data, available through the National Oceanic and Atmospheric Administration (NOAA), was used to understand and characterize spatial and temporal precipitation patterns across the watershed during individual storm events.

The six step process of defining these zones and developing the time-series from rain gage and NEXRAD data is itemized as follows.

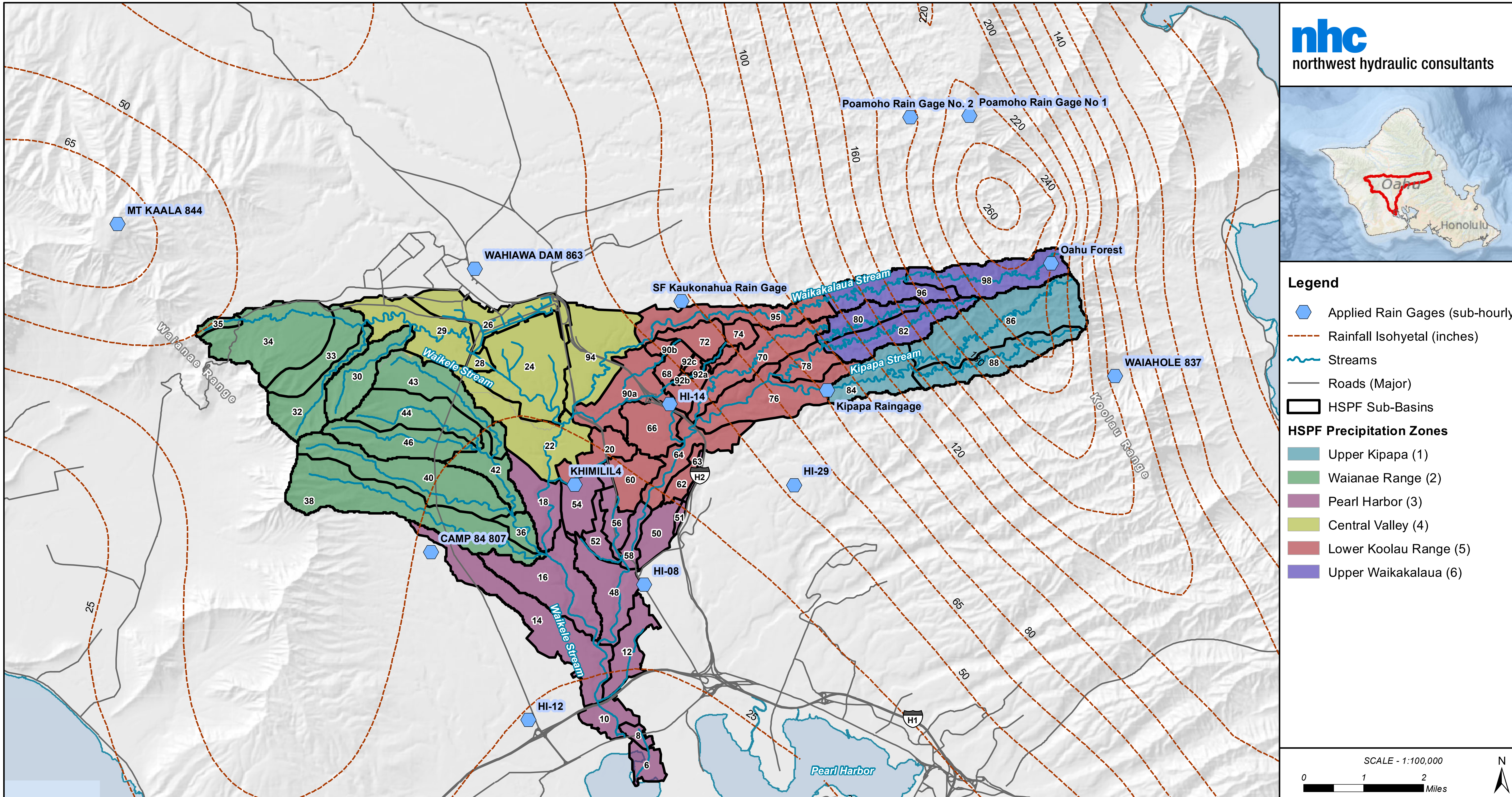
1. Six precipitation zones were identified based on mean annual precipitation and topography and subbasin boundaries.
2. Raster datasets of annual average rainfall covering the Island of Oahu were obtained from the Oregon State University PRISM Climate Group (PRISM) and used to identify the area weighted average annual precipitation for each precipitation zone.
3. Each of the six precipitation zones was associated with one of the actual rain gage sites for purposes of correlation.
4. A synthetic record for each of the six zones was creating by multiplying the hourly values at the corresponding actual rain gage site by ratio of zonal average annual rainfall to actual average annual rainfall (per PRISM).
5. The zonal records from the above Step 4 were adjusted by replacing data for selected storms with NEXRAD data representing hourly average rainfall over four of the six zones (zone numbers 1, 2, 4, and 6). NEXRAD data was not used in Zones 3 and 5 where rain gage coverage is relatively good.

As stated above, the precipitation time-series for each zone utilizes the record of the most applicable ground rain gage, except for the selected storms listed in Table 4 when average hourly zonal rainfall was computed from NEXRAD data (for four of the six zones). Rain gages were matched to precipitation zones based on the proximity of the gage to the centroid of the zone, annual rainfall total similarity, and orthographic effects. A map of average annual precipitation isohyetals available from the PRISM Climate Group at Oregon State University (PRISM, 2000) was used to calculate an average annual precipitation over the subbasin and at the location of each rain gage. The ratio of these two precipitation values was used to calculate a multiplier to transpose the rain gage record for use as a time-series applied to each precipitation zone. Table 2 summarizes the rain gage and aerial weighting multipliers derived from the PRISM dataset that were applied for each precipitation zone. Rain gages listed in Table 3 that are not included in Table 2 were used to fill gaps in the primary gage records.

Table 2: Precipitation Zone Rain Data Factors

Precipitation Zone Name (ID)	Area (acres)	Rain Gage Time-Series (for non-NEXRAD data periods)	Rain Gage Avg. Annual Precip. from PRISM Isohyetal Map (in)	Zone Avg. Annual Precip. from PRISM Isohyetal Map (in)	Multiplier to Transpose Rain Gage Record to Zone
Upper Kipapa (1)	2645.8	Poamoho No. 2	211.09	182.50	0.86
Waianae Range (2)	8321.2	Wahiawa Dam	49.74	44.03	0.89
Pearl Harbor (3)	3692.7	KHIMILIL4[1]	32.60	26.82	0.82
Central Valley (4)	7666.8	Wahiawa Dam	49.74	47.47	0.95
Lower Koolau Range (5)	5264.1	Kipapa	99.73	64.40	0.65
Upper Waikakalaua (6)	2300.8	Poamoho No. 2	211.09	165.90	0.79

[1] HI-12 was used for most of this gage record.



Coordinate System: NAD 1983 HARN STATEPLANE HAWAII 3 FIPS 5103 FEET

Job: 21831 | Date: 04-Apr-2017

Central Oahu Watershed Study

HSPF Model Precipitation Zones and Gages

FIGURE 3

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Table 3: Rain Gage Locations

Station Name	Agency	Latitude	Longitude	Elev. (feet)	Annual Precip. from PRISM Isohyetal Map (in)	Years Record Available
Camp 84	NWS - NCDC	21.42778	158.06111	780	35.9	1978-current
Wahiawa Dam	NWS - NCDC	21.49667	158.04972	854	49.7	1965-current (large gaps '02-'04)
Waiahole	NWS - NCDC	21.47056	157.88361	745	230.1	1965-current
Mt. Kaala	NWS - NCDC	21.5075	158.1425	4010	71.1	1965-current
Poamoho No. 1	USGS	21.53386	157.92138	2480	206.7	1967-1998[1] 1997-current[2] 2008-current[3]
Poamoho No. 2	USGS	21.53341	157.93669	1960	211.1	1992-1996[1] 1997-current[2] 2008-current[3]
Kipapa	USGS	21.46710	157.95836	690	99.7	1992-1994 (daily) 1994-1995 (30-min) 1999-2004 (15-min)
Kaukonahua	USGS	21.48880	157.99605	860	74.5	2005-current
Oahu Forest (OFRH1)	USFWS	21.49944	157.90027	2293	223.9	2006-2015
HI-29 - Waiawa CF	NWS - Hydronet	21.444099	157.9669	773	58.8	1994-2013 (Hydronet) 2014-current (UANet)
HI-14 - Mililani	NWS - Hydronet	21.4638	157.9991	744	51.0	1994-2013 (Hydronet) 2014-current (UANet)
HI-12 - Kunia	NWS - Hydronet	21.386999	158.0358	279	25.6	1994-2013 (Hydronet) 2014-current (UANet)
HI-08 - Waipio	NWS - Hydronet	21.4199	158.0058	410	32.1	1994-2013 (Hydronet) 2014-current (UANet)
KHIMILI4[2]	Weather Underground	21.444	158.024	617	32.6	October 2007 – July 2010

[1]Float System, daily only, [2]Float System, 15 or 30 minute, [3]Tipping Bucket System, 15 -minute
[2] http://www.wunderground.com/personal-weather-station/dashboard?ID=KHIMILIL4#history/tdata/s20081211/e20081211/mdaily

2.1.1 Koolau Range Rain Gages

There is a notable absence of rain gages in the upper portions of the watershed within the Koolau Range where most of the study area rainfall occurs. The gages that are the most representative of the upper Koolau subbasins are the Oahu Forest gage operated by the USFWS, Poamoho No. 1 and No. 2 (see Photo 8) operated by the USGS, and to a lesser extent, the Waiahole gage operated by the NWS. The Waiahole gage is closer to the study area than the other three gages but is located on the east side of the Koolau range crest, and as a result, many of the rainfall patterns did not match those of the upper study area subbasins. The Kipapa gage operated by the USGS is also in close spatial proximity, but is located well below the subbasin headwaters and measurements were discontinued in 2004. The two Poamoho gages are in close proximity to one another and have similar records.

Photo 8: USGS Poamoho Rain gage No. 2 (December, 2009).

2.1.2 Lower Waikele and Mililani Region Rain Gages

As mentioned later in Section 4.1, precipitation data in the Mililani region was closely critiqued as part of model calibration to the Mililani Storm Drain A flow data. Of specific interest was the December 11, 2008 event. Figure 4 presents eight different time-series of precipitation data recorded for that event at known rain gages closest to the Mililani subbasin. Unlike typical precipitation gradients in the region, which have higher rainfall volumes on the east side of the basin, this storm had a large south to north gradient with the highest volumes recorded at Wahiawa Dam on the north edge of the Waikele Watershed. Two local rain gages, KHIMILIL4 and HI-12 (in orange and purple) below, were found to be superior to the NEXRAD record in this area and were combined for use as the Zone 3 precipitation record, which includes the Mililani subbasin.

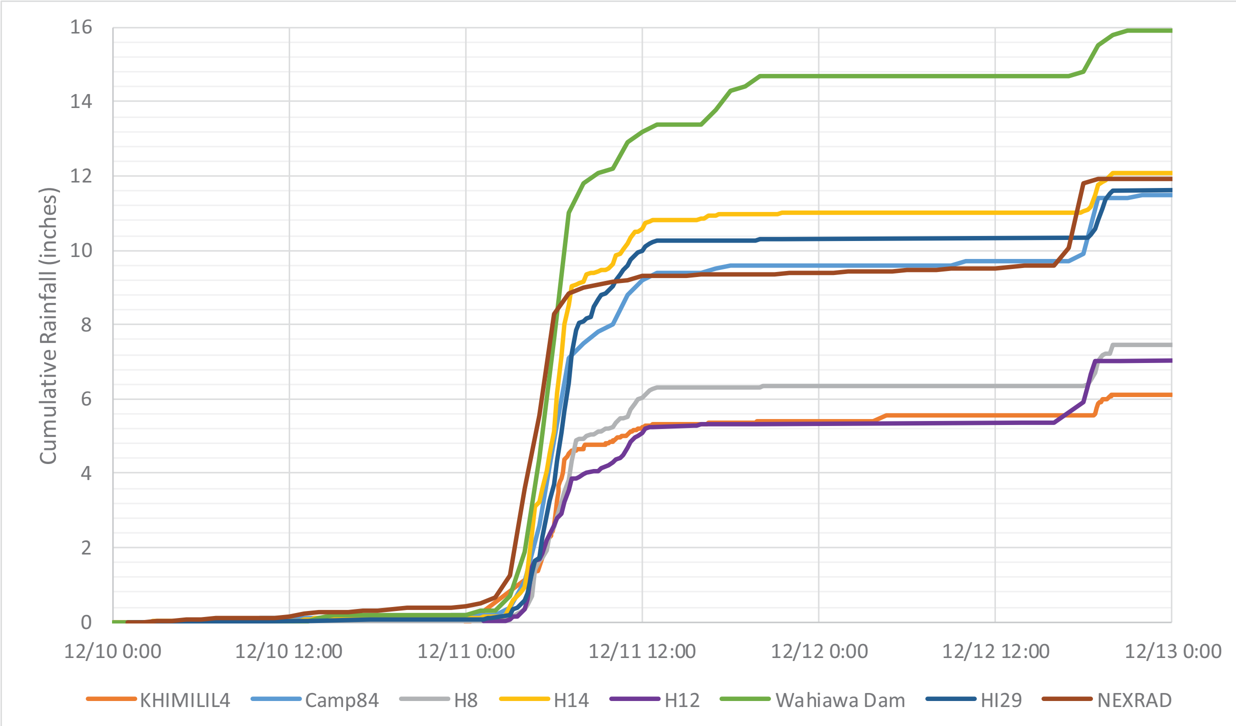


Figure 4: Detailed Review of Precipitation in Mililani Region for the December 11, 2008 Storm

2.2 NEXRAD Radar Precipitation Data Review

The utilized NEXRAD data product is a time-series of gridded precipitation data which captures the movement of specific storm events through the watershed and can be checked for consistency with ground rain gage data. The NEXRAD time-series datasets are collected from nearby weather radars and include a number of parameters based on reflectivity observed by the radar instrument. The data product used in this study is the one-hour precipitation totals called N1P by NOAA. Weather radars currently operating near the study area are Molokai (PHFO) and South Kauai (PHKI). Each of these instruments collects weather data within a 150 mile radius around the radar site. The radar is pointed upward above the horizon, and as a result, the sampled weather is representative of a specific elevation above the earth depending on the distance from the radar antenna. Data available for the study area is at an elevation of 4,000 feet from the Molokai instrument and 6,000 to 10,000 feet from the South Kauai instrument. For the Waikele watershed, the Molokai station was selected for use because data recorded closest to the ground is the most representative of rainfall that fell on the watershed. There is a significant amount of data processing required to use NEXRAD data for hydrologic modeling, so only key storm events were selected that coincided with high flows observed within the study area. After initial processing of the NEXRAD data, the data had to be checked to see if it correlated with the ground gage record and was usable for calibration of the HSPF model. These checks required processing the

NEXRAD precipitation grids[1] into a time-series of precipitation at the coordinates of each rain gage. The Oahu Forest and NWS Hydronet rain gages were not available at the time the NEXRAD data was processed in 2010, and they are excluded from this comparison, originally documented in PB-NHC (2010). Table 4 below provides a summary of ratings of the quality of the NEXRAD data at each rain gage for each storm event. Ratings are based on how well the estimated NEXRAD data for the grid cell containing the rain gage compared to the actual observed precipitation at that gage site. The ratings are partitioned into one of three general categories: good, marginal, and poor. Ratings of "good" (NEXRAD storm differs by less than 0.5 inches compared to rain gage storm total OR < 15 percent of total storm precipitation volume and good match of timing) and "marginal" (< 1.0 inches OR < 15 percent, timing may be off but total depth matches are within the specified criteria.). Comparisons not meeting "good" or "marginal" criteria were rated as "poor". Blank cells in the table indicate that no data are available for either the rain gage or radar during that event. The second column in the table identifies the storm events used in the calibration.

Table 4: Comparison of NEXRAD Radar and Rain Gage Data Precipitation

Event Date	NEXRAD Data Used for Hydrology Calibration	Ratings of NEXRAD Comparison with Observed Rain Gage Data							
		Camp 84	Wahiawa Dam	Waiahole	Kipapa	Kaukonahua	Poamoho No. 1	Poamoho No. 2	Mt. Kaala
3/17/91	No								
10/16/91	No								
1/29/02	No	○	○	○	○		◑		○
3/07/02	Yes	●	●		◑		N/A [1]	●	○
5/06/02	No								
12/7/03	No	◑		N/A	●		○	●	N/A
3/23/04	No	N/A	N/A	○	◑	N/A	◑	●	N/A
10/1/05	Yes		●			●	◑	N/A [2]	◑
6/03/07	No	N/A	●	N/A		◑	◑	○	○
11/04/07	Yes	●	○	●		●	●	●	○
12/05/07	Yes	●	●			●	●	◑	
2/07/08	Yes	●	◑	○		○	●	●	
12/11/08	Yes	◑	◑	◑		◑	◑	◑	● [1]

○ Poor
◑ Marginal
● Good

[1] Rain Gage Data is Suspect
[2] no Rain Gage data available during peak of event

[1] The NEXRAD precipitation grids are provided by the NWS as a series of 6-minute datasets of hourly rainfall totals that are grouped by day. Data grid cells are 15-arc seconds (~1400 feet or 430 meters) square. Precipitation time-series were interpolated at even hour intervals from these six-minute datasets. Rainfall intensities less than 0.1 inches per hour are grouped by the NWS into a single trace bin. Values for this bin were assigned the average of the bin of 0.05 inches per hour.

2.3 Additional Meteorologic Data

HSPF model simulations require time-series of six other meteorological time-series including: potential evapo-transpiration, air temperature, solar radiation, dew point temperature, average wind speed, and cloud cover, as summarized in Table 5 below. Precipitation is also a meterological parameter but it was discussed in detail in the previous section. Most meteorological time-series used for the HSPF model were recorded at the Honolulu Airport (HNL), the only exceptions being pan evaporation and cloud cover which were recorded at the Honolulu Observatory and Wheeler Army Air Force (AAF) station, respectively. Potential evapo-transpiration from the land surface and from streams in the model is estimated by applying a multiplier of 0.78 to the recorded pan evaporation data. This multiplier value is similar to those used for HSPF model applications in the Pacific Northwest of the continental U.S. Some error in this multiplier value is acceptable because the hydrologic model is calibrated by adjusting the volume of intercepted rainfall that is lost to ground water, a compensating process that when combined with evapo-transpiration completes the water-balance and ensures that the model simulates observed stream volumes. Monthly average values were used to fill missing periods of pan evaporation data. Solar data for the period 1986 through 2004 was acquired from the NOAA Mauna Loa Observatory (MLO) station located near Hilo, HI. Data has been collected at the same location under a slightly different program since 2004, but data requests to NOAA were not completed prior to publication of this document. Instead, the pre-2004 data was shifted forward 10 years to cover the period 1996 through 2014 needed for calibration and production runs. Because the solar radiation in Hawaii are relatively consistent, and the variables currently activated in the HSPF model are not particularly sensitive to solar radiation, this shift provides data needed for the current modeling effort. Solar radiation is most critical when simulating growth involving photosynthesis of algae or macrophytes; neither of which are addressed by the current study.

Table 5: Meteorological Data Sources

Parameter Name (HSPF acronym)	Units	Location	DSN ID	Period
Pan Evaporation (estimate for PETINP and POTEV)	Inches	Observatory	26	’79 – ‘09
Air Temperature (GATEM)	Degrees F.	HNL Airport	19	’89 – ‘09
Solar Radiation (SOLRAD)	W / meter^2	MLO	15	’76 – ‘04
Dew Point Temperature (DEWTMP)	Degrees F.	HNL Airport	23	’89 – ‘09
Average Wind Speed (WIND)	Miles per Hour	HNL Airport	21	’89 – ‘09
Cloud Cover (CLOUD)	Percent	Wheeler AAF	18	’89 – ‘09

3 MODEL SEGMENTATION AND DEVELOPMENT

3.1 PERLND and IMPLND Numbering Scheme

The HSPF model framework represents the diversity of land management or use, precipitation, land cover, soils and topography within watershed subbasins using a set of hydrologic response units known as PERLNDs (pervious land segments) and IMPLNDs (impervious land segments). Each IMPLND or PERLND is defined by a set of model parameters representing a unique runoff and pollutant generation type, into which subbasin acreages are classified. Acreages of the same IMPLND or PERLND can occur in more than one subbasin and contribute to more than one RCHRES (stream channel segment) as long as those acreages all have sufficiently similar soil, slope, management, receive similar amounts of rainfall and have similar runoff and pollutant generation potential. The model is run for each unit. Runoff and pollutant contributions to each stream channel are then based on the acreage of each IMPLND or PERLND in each subbasin.

The PERLND and IMPLND numbering scheme applied for the Waikele Watershed is similar to other HSPF models DFM-SWQ has used or is using on Oahu (e.g. the Ala Wai and Kiikii Stream Watersheds). The model response units were configured to differentiate areas based on land cover, land use, soil type, and precipitation zone. Topography/slope was not used to differentiate response units because slope and soil type are often associated. In order to systematically assign unique identifiers (IDs) to the three digits allowed by HSPF, the following scheme was developed: The first two digits of the PERLND/IMPLND ID is assigned a land cover/land use/soil ID, and the third digit a precipitation zone ID. The precipitation zone IDs were listed previously in Table 2, and the IMPLND and PERLND land use, land cover, and/or soil IDs are listed in Table 6 and Table 7, respectively. The data sources and further explanation of the attributes in these tables is discussed in detail below.

Table 6: Land Use IMPLND Response Unit IDs

IMPLND ID	Land Use	Land Cover	Formal Street Sweeping Plan
1X	Low-Pollution Generating	Impervious Surface	None
2X	High-Pollution Generating	Impervious Surface	None
3X	High-Pollution Generating	Impervious Surface	City and County of Honolulu
4X	High-Pollution Generating	Impervious Surface	Hawaii Department of Transportation

Table 7: Land Use / Land Cover / Soil PERLND Response Unit IDs

PERLND ID	Land Use	Land Cover	Soil
10X	Conservation	Forest	Koolau/Waianae Mountain Soil, Low-Runoff
11X	Conservation	Forest	Koolau Mountain Soil, High-Runoff
12X	Conservation	Forest	Rock Valley Soils
13X	Conservation	Forest	Steep Valley Silty Clay Soil
14X	Conservation	Forest	Other Valley Silty Clay Soil
15X	Urban	Forest	Koolau/Waianae Mountain Soil, Low-Runoff
16X	Urban	Forest	Koolau Mountain Soil, High-Runoff
17X	Urban	Forest	Rock Valley Soils
18X	Urban	Forest	Steep Valley Silty Clay Soil
19X	Urban	Forest	Other Valley Silty Clay Soil
20X	Low-Density Residential	Grass	Koolau/Waianae Mountain Soil, Low-Runoff
21X	Low-Density Residential	Grass	Koolau Mountain Soil, High-Runoff
22X	Low-Density Residential	Grass	Rock Valley Soils
23X	Low-Density Residential	Grass	Steep Valley Silty Clay Soil
24X	Low-Density Residential	Grass	Other Valley Silty Clay Soil
25X	High-Density Residential	Grass	Koolau/Waianae Mountain Soil, Low-Runoff
26X	High-Density Residential	Grass	Koolau Mountain Soil, High-Runoff
27X	High-Density Residential	Grass	Rock Valley Soils
28X	High-Density Residential	Grass	Steep Valley Silty Clay Soil
29X	High-Density Residential	Grass	Other Valley Silty Clay Soil
30X	Commercial	Grass	Koolau/Waianae Mountain Soil, Low-Runoff
31X	Commercial	Grass	Koolau Mountain Soil, High-Runoff
32X	Commercial	Grass	Rock Valley Soils
33X	Commercial	Grass	Steep Valley Silty Clay Soil
34X	Commercial	Grass	Other Valley Silty Clay Soil
40X	Conservation	Scrub-Shrub	Koolau/Waianae Mountain Soil, Low-Runoff
41X	Conservation	Scrub-Shrub	Koolau Mountain Soil, High-Runoff
42X	Conservation	Scrub-Shrub	Rock Valley Soils
43X	Conservation	Scrub-Shrub	Steep Valley Silty Clay Soil
44X	Conservation	Scrub-Shrub	Other Valley Silty Clay Soil
45X	Urban	Scrub-Shrub	Koolau/Waianae Mountain Soil, Low-Runoff
46X	Urban	Scrub-Shrub	Koolau Mountain Soil, High-Runoff
47X	Urban	Scrub-Shrub	Rock Valley Soils
48X	Urban	Scrub-Shrub	Steep Valley Silty Clay Soil
49X	Urban	Scrub-Shrub	Other Valley Silty Clay Soil
50X	Pasture		Koolau/Waianae Mountain Soil, Low-Runoff
51X	Pasture		Koolau Mountain Soil, High-Runoff
52X	Pasture		Rock Valley Soils
53X	Pasture		Steep Valley Silty Clay Soil
54X	Pasture		Other Valley Silty Clay Soil
55X	Golf-Course		Koolau/Waianae Mountain Soil, Low-Runoff
56X	Golf-Course		Koolau Mountain Soil, High-Runoff
57X	Golf-Course		Rock Valley Soils
58X	Golf-Course		Steep Valley Silty Clay Soil
59X	Golf-Course		Other Valley Silty Clay Soil
60X	Bare Earth		Koolau/Waianae Mountain Soil, Low-Runoff
61X	Bare Earth		Koolau Mountain Soil, High-Runoff
62X	Bare Earth		Rock Valley Soils
63X	Bare Earth		Steep Valley Silty Clay Soil
64X	Bare Earth		Other Valley Silty Clay Soil
70X	Agricultural Road		Koolau/Waianae Mountain Soil, Low-Runoff
71X	Agricultural Road		Koolau Mountain Soil, High-Runoff

PERLND ID	Land Use	Land Cover	Soil
72X	Agricultural Road		Rock Valley Soils
73X	Agricultural Road		Steep Valley Silty Clay Soil
74X	Agricultural Road		Other Valley Silty Clay Soil
75X	Seed Corn		Koolau/Waianae Mountain Soil, Low-Runoff
76X	Seed Corn		Koolau Mountain Soil, High-Runoff
77X	Seed Corn		Rock Valley Soils
78X	Seed Corn		Steep Valley Silty Clay Soil
79X	Seed Corn		Other Valley Silty Clay Soil
80X	Truck Crop		Koolau/Waianae Mountain Soil, Low-Runoff
81X	Truck Crop		Koolau Mountain Soil, High-Runoff
82X	Truck Crop		Rock Valley Soils
83X	Truck Crop		Steep Valley Silty Clay Soil
84X	Truck Crop		Other Valley Silty Clay Soil
85X	Pineapple		Koolau/Waianae Mountain Soil, Low-Runoff
86X	Pineapple		Koolau Mountain Soil, High-Runoff
87X	Pineapple		Rock Valley Soils
88X	Pineapple		Steep Valley Silty Clay Soil
89X	Pineapple		Other Valley Silty Clay Soil
90X	Any		Saturated/Wetland Soil

3.1.1 Existing Land Use

Figure 5 shows current land use in the Waikele Watershed, based on current tax parcel data[2]. The three main land uses are forest conservation, agriculture, and urban development. Designated forest conservation land is the primary use in the steep upper watersheds of the Koolau and Waianae Ranges. Most of the developed impervious land use is located on the eastern side of the Oahu plain, in urban areas such as Mililani Town and Wahiawa. Both the Schofield Barracks and Wheeler AAF military installations also contribute developed areas along the northern boundary of the watershed. Agriculture is predominantly located on the western edge of the Oahu Plain near the Waianae Gulches and Waikele Stream. Kipapa Stream has small areas of agriculture along its eastern border.

Chapter 2 of the Waikele Stream Geomorphic Assessment (NHC, 2016), included as Appendix A, provides further discussion of the existing basin land use (Section 2.7) and historic changes in the land use that are relevant to sediment transport through the watershed (Section 2.8). Two key ongoing changes that began in the last half of the 1900s are the shifts in central valley land uses away from the cultivation of pineapple and sugar cane to urban or new diversified agriculture crops (e.g. Fischer, 2006 and Gomez, 2008). This change to diversified agriculture is of concern because those crops (e.g. seed corn and truck crops) have been shown to generate higher sediment loads than legacy pineapple and sugar cane plantation crops (e.g. El-Swaify, 2002).

Five unique agricultural crops were delineated and modeled as unique HSPF cover groups so different nutrient and sediment management practices can be represented by the model. Only limited information about different loading characteristics from these crops types currently exists, but research into diversified agriculture on Oahu is expected to allow further refinement in the future. A sixth agricultural cover group called 'Ag. High Runoff' was created to represent roads and other compacted

[2] City and County of Honolulu GIS table "Facilities2010", field "FacilityCo"

areas; this category is non-spatial and represents 30 percent of the five crop types. Additional discussion of this group is included in the hydrologic calibration discussion.

Table 8 is a lookup table allowing tax parcel use codes to be mapped to HSPF model land use or land management category names. The road right-of-way and large parking lot areas were characterized as high-pollution generating surface. Road right-of-way was defined from the City and County of Honolulu's GIS polygons, and large parking lot areas were manually delineated from orthophotos. Right-of-way areas are additionally characterized with ownership and street sweeping attributes that are utilized as part of the HSPF representation of street sweeping, discussed further in Section 3.5.

Table 8: Tax Parcel Land Use to HSPF Land Use Category Lookup Table

HSPF Land Use ID	HSPF Land Use / Management Category Name	Tax Parcel Use Category
1	Commercial-Industrial	Hotel, Office, Retail, Services, Production/Storage/Distr, Utilities, Educational/Cultural, Public Safety, Hospital, Transit Terminal, Exhibition, Sports, Worship
2	High Density Residential	Building, Townhouse, Apartment, Group Quarter
3	Low/Medium or High Density Residential[1]	Single Family, Ancillary Dwelling
4	Open Space[2]	Open Recreation, Other Open Facility
5	Golf Courses[3]	Golf Courses
6	Conservation[4]	
7	High Pollution Generating Impervious Surfaces, Swept by HDOT	Road Right-of-Way[5]
8	High Pollution Generating Impervious Surfaces, Swept by CCH	
9	High Pollution Generating Impervious Surfaces, Not Swept	
10	Pasture	Agriculture[6]
11	Fallow	
12	Pineapple	
13	Seed Corn	
14	Truck Crop	

[1] Single family parcels were classified as Low/Medium Density Residential if the dwelling unit (DU) density was calculated to be less than 6.5 DU/acre. Densities greater than 6.5 DU/acre were classified as high density.
[2] Parcels with "Preservation" in both the "DP Desc" and "LU Desc" fields were also categorized as Open Space.
[3] Most of the classified as Golf Course were mapped by the C-CAP dataset as 'Open Spaces Developed' but small areas of 'Scrub/Shrub' and other C-CAP covers are also included.
[4] Conservation lands are specified by the State of Hawaii.
[5] Road Right-of-Way area is not included in the parcel dataset. These areas were added from other City and County of Honolulu GIS datasets including roadway ownership and street sweeping plans. Large parking lots were manually delineated from aerial orthophotos.
[6] Agricultural land uses were manually delineated by DOH/EPA staff. Minor modifications in the Upper Waikele basin were also made by NHC staff during model calibration based on review of orthophotos. Most of the areas classified as Agriculture were mapped by the C-CAP dataset as 'Cultivated lands' but small areas of 'Grassland' and other C-CAP covers are also included.

3.1.2 Existing Land Cover

Figure 6 shows the land cover in the watershed as of 2005. The largest four land covers within the 45 square mile study area include evergreen forest (21.4 square miles), cultivated lands (8.4 square miles) and developed areas (9.9 square miles). Most of the forested areas are located on the slopes of the Koolau and Waianae mountain ranges, which are designated and managed as conservation areas. Most of the developed impervious land use is located in the central valley portion of the study area, which includes Mililani Town, Wahiawa, and both the Schofield Barracks and Wheeler AAF military installations.

Land cover was primarily defined using the C-CAP data product from the NOAA. This is available as a GIS raster format with 2.4 meter pixel resolution. In addition to C-CAP, the City and County of Honolulu GIS rooftop polygon dataset was used to further characterize impervious surfaces into categories based on their pollution generation potential, and High and Low Pollution Generating Impervious Surfaces (HPGIS and LPGIS, respectively). Any non-rooftop impervious surfaces (primarily roadways and parking lots) were characterized as HPGIS. Land cover for some areas where significant development occurred since 2005 where manually updated from 2011 orthophotos. Table 9 is a lookup table between C-CAP land cover category names and HSPF model land cover category names.

Table 9: C-CAP Land Cover to HSPF Land Cover Category Lookup Table

HSPF Land Cover Category ID	HSPF Land Cover Category Name	C-CAP Image Category Name
1	Exposed Soil (non-cultivated)	Unconsolidated Shore, Bare Land
2	Forest	Deciduous Forest, Evergreen Forest
3	Grass	Open Spaces Developed, Unclassified
4	Scrub-Shrub and Grassland	Grassland, Scrub/Shrub
5	Wetland and Water	Water, Palustrine Forested Wetland, Palustrine Scrub/Shrub Wetland, Palustrine Emergent Wetland, Estuarine Forested Wetland, Estuarine Scrub/Shrub Wetland, Estuarine Emergent Wetland, Palustrine Aquatic Bed
6	High Pollution Generating Impervious Surface (with or without sweeping)	Non-rooftop impervious surfaces (i.e. roadways, parking lots, and driveways) [1]
7	Low Pollution Generating Impervious Surface	Rooftop impervious surfaces[1]
8	Agriculture	Cultivated Land, Pasture/Hay,

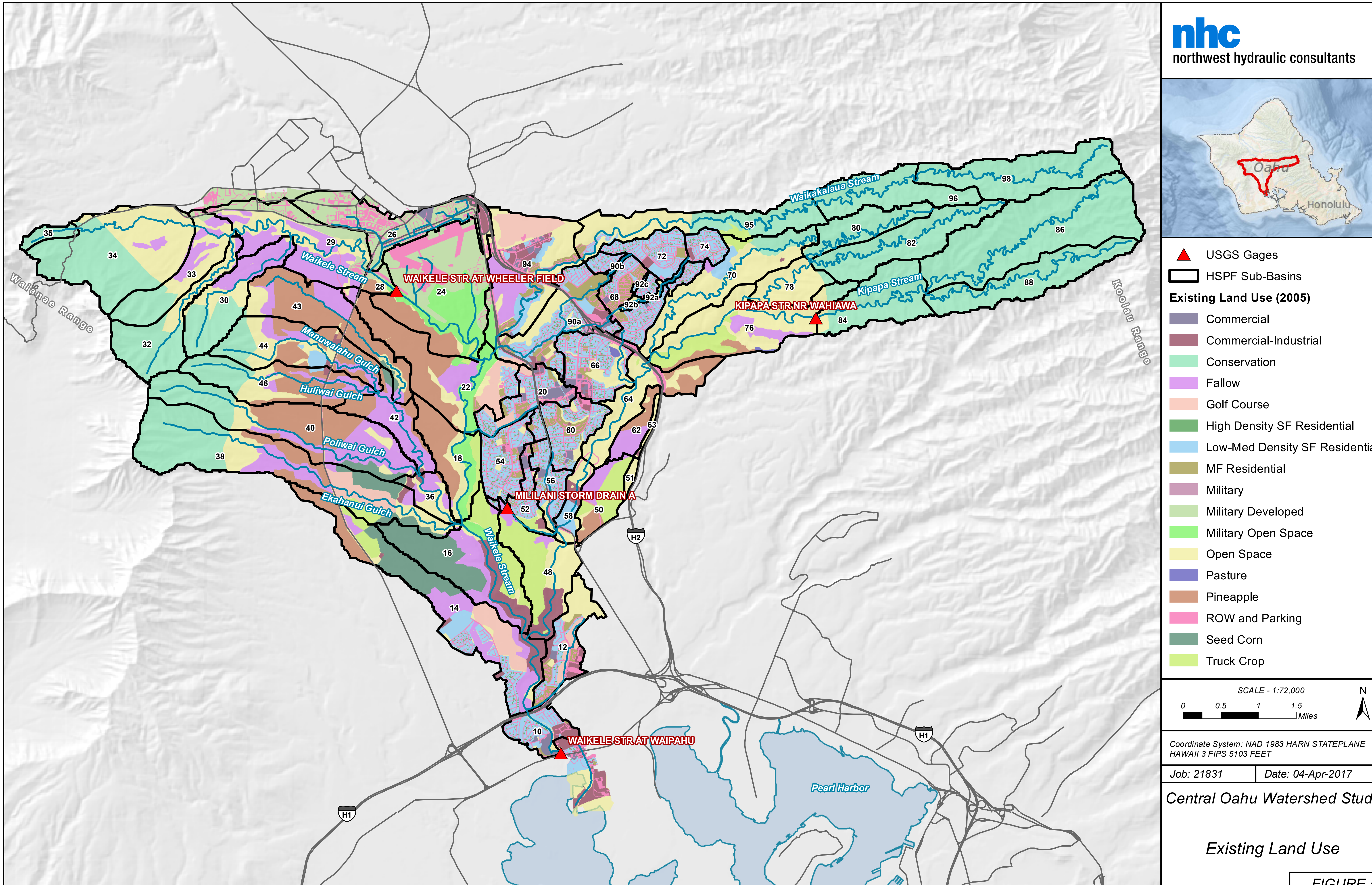
[1] C-CAP does not distinguish rooftop from non-rooftop impervious surface. The City and County of Honolulu rooftop polygon GIS dataset was added to the C-CAP imagery to allow further classification of impervious surfaces as high or low pollution generating impervious surfaces.

Effective Impervious Area

For modeling purposes only, a portion of impervious surfaces are assumed to be effectively connected to the storm drain system. This area is referred to as Effective Impervious Area (EIA). The remaining fraction of impervious area that is not effective is modeled as grass. An single set of connectedness values (the EIA/TIA ratio) was applied study area-wide. During the process of model calibration to observed flows leaving basin 28, it was determined that three Upper Waikele Stream basins have lower effective impervious areas than the remainder of the study area. These two sets of EIA/TIA ratios are shown in the right two columns of Table 10.

Table 10: Impervious Connectedness by Land Use

HSPF Land Use / Management Category Name	Impervious Area EIA/TIA Ratio (Percent Connected)	
	Upper Waikele[1]	All Other Basins
Commercial-Industrial	80%	90%
High Density Residential	70%	80%
Low/Medium or High Density Residential	25%	50%
Open Space	10%	50%
Truck Crops, Seed Corn, Pineapple, and Fallow Agriculture	10%	50%
Conservation	10%	50%
High Pollution Generating Impervious Surfaces, Swept by HDOT	80%	90%
High Pollution Generating Impervious Surfaces, Swept by CCH	80%	90%
High Pollution Generating Impervious Surfaces, Not Swept	80%	90%
[1] Upper Waikele Stream Basins 24, 26, and 28 have reduce impervious area connectedness, see calibration discussion.		


nhc
northwest hydraulic consultants
Oahu
Honolulu
USGS Gages
HSPF Sub-Basins
Existing Land Use (2005)
Commercial
Commercial-Industrial
Conservation
Fallow
Golf Course
High Density SF Residential
Low-Med Density SF Residential
MF Residential
Military
Military Developed
Military Open Space
Open Space
Pasture
Pineapple
ROW and Parking
Seed Corn
Truck Crop
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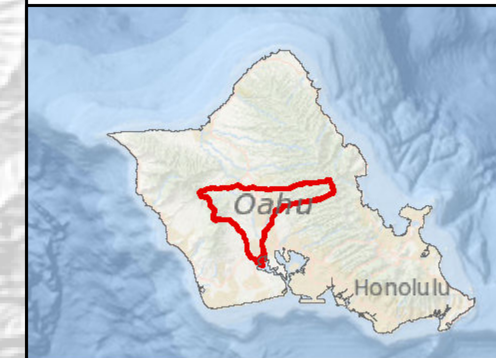
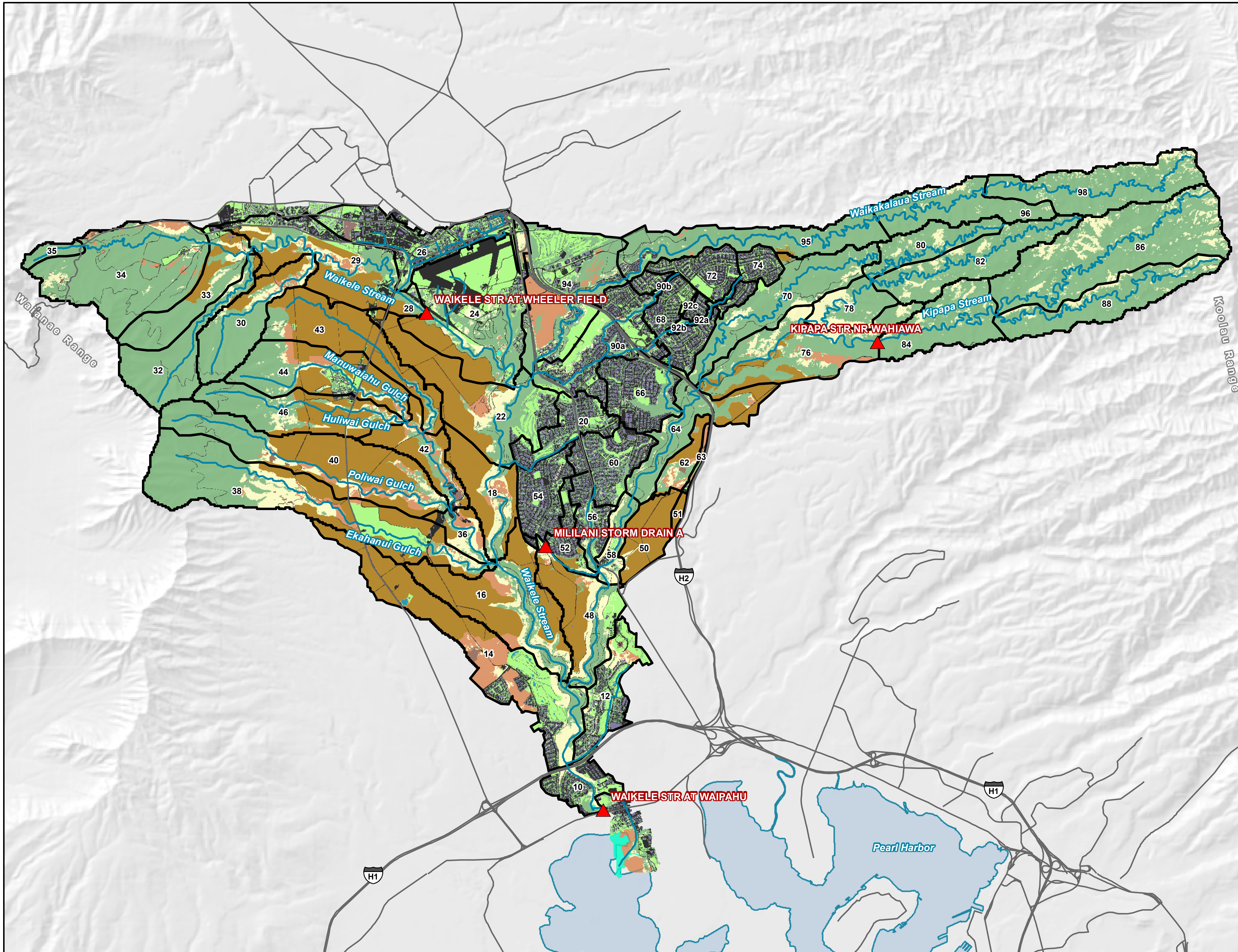
Job: 21831
Date: 04-Apr-2017
Central Oahu Watershed Study
Existing Land Use
FIGURE 5
WAIKELE STR AT WHEELER FIELD
KIPAPA STR NR WAHIAWA
MILILANI STORM DRAIN A
WAIKELE STR AT WAIPAHU
Waikakalaua Stream
Kipapa Stream
Waikele Stream
Manuwaiahu Gulch
Huliwai Gulch
Poliwai Gulch
Ekahanui Gulch
Waianae Range
Koolau Range
Pearl Harbor
H1
H2

northwest hydraulic consultants





Legend

- USGS Gages
- HSPF Sub-Basins

Existing Land Cover (2005)

- Rooftop
- Impervious Surface
- Grass
- Cultivated Land
- Bare Land
- Grassland
- Evergreen Forest
- Scrub/Shrub
- Wetland
- Water

SCALE - 1:72,000

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Job: 21831	Date: 04-Apr-2017

Central Oahu Watershed Study

Existing Land Cover

FIGURE 6

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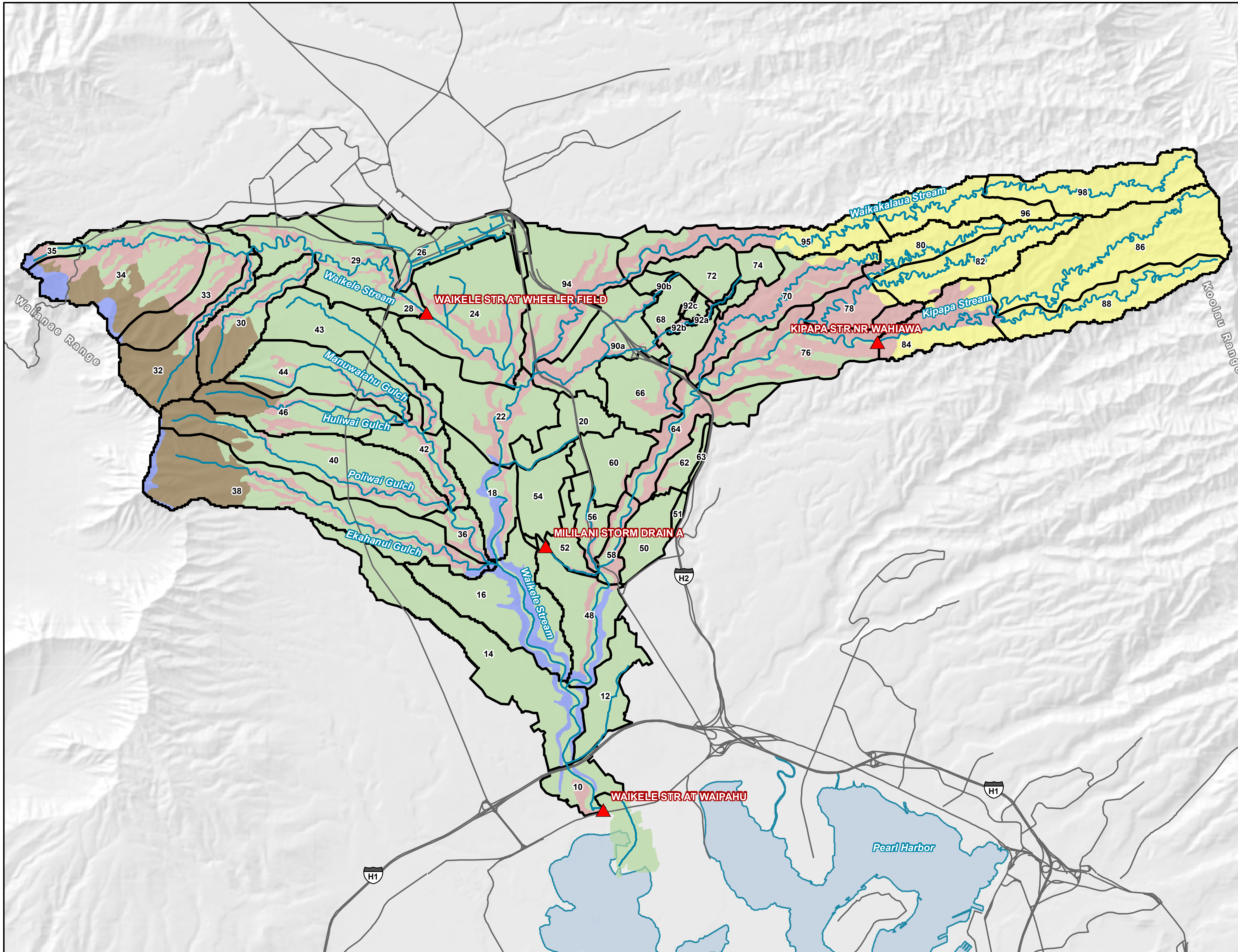
3.1.3 Soils

The hydrologic response of pervious surfaces is controlled by the surface soils and the underlying geology of the subbasin. According to Yamamoto (1963), water retention properties are high for all Hawaiian soils. While some clay textured soils have a low permeability, Lau and Mink (2006) state that Hawaiian clay-texture soils with a strong aggregate structure—such as the Wahiawa series—are as permeable as sand and explain that water retention values typical for Hawaiian soils exceed those of all reference soils (by texture) in the continental U.S. The water retention properties of undisturbed soils will be reduced by the effects of land use; forest soils having the highest porosity (66 to 90 percent) and agricultural lands having much lower [a few to eight percent] (Yamamoto, 1963). Study area soils were characterized using the Soil Survey Geographic database (SSURGO), a GIS-based polygon coverage of soil classifications by NRCS (2008). Detailed descriptions of each soil classification are include in a database distributated with SSURGO and are also included with regional NRCS soil reports. There are dozens of NRCS soil types within the Waikele Stream watershed. For the purposes of the HSPF model, these soils have been grouped into the five categories shown in Table 11. The soil types include two silty-clay categories, valley rock land, Waianae mountain soils, and the Koolau mountain soils; each HSPF model soil type has a similar hydrologic soil characteristic based on the SSURGO database. The soil types were chosen based on the following:

- **Other Silty-Clay** soil type includes all non-mountain soils accept those included in Steep Silty-Clays and Valley Rock Lands.
- **Steep Silty-Clays**, exclusively NRCS Helemano silty clays with 30 to 90 percent slopes, were distinguished from all other silty-clay soils because they have markedly steeper slopes and they cover a large percentage of the study area.
- **Valley Rock Lands** are the only non-mountainous NRCS soil type with any significant area that is not similar to a silty-clay.
- **Waianae** and **Koolau Mountain Soils** each have unique geology and were modeled as unique soils types. As discussed in the calibration section of this report, the Koolau Mountain soil type was modeled as both a high and low runoff land surface.

Table 11: Representation of NRCS Soils within Waikele Stream HSPF Model

NRCS SSURGO		HSPF Model	
NRCS Soil Type	% of Study Area	HSPF PERLND Soil Group	% of Study Area
Rough mountainous land	16.8	Koolau \ Waianae Mountain Soil – Low Runoff	14.6
		Koolau Mountain Soil – High Runoff	2.2
Tropohumults-Dystrandepts association	7.0	Waianae Mountain Soil	7.0
Helemano silty clay (30 to 90 percent)	18.1	Steep Silty-Clays	17.1
Rock Land	2.4	Valley Rock Land Soil	2.3
Wahiawa silty clay (0 to 15 percent)	21.4	Other Silty-Clays	44.3
Kunia silty clay (0 to 15 percent)	9.4		
Kolekole silty clay loam (1 to 25 percent)	3.9		
Lahaina silty clay (0 to 15 percent)	3.7		
Molokai silty clay loam (0 to 25 percent)	3.6		
Leilehua silty clay (2 to 12 percent)	2.8		
Kawaihapai clay loam (0 to 15 percent)	1.9		
Fill land	1.9		
Haleiwa silty clay (0 to 6 percent)	1.9		
Manana silty clay loam (6 to 35 percent)	1.6		
Manana silty clay (3 to 25 percent)	0.9		
Kemoo silty clay (12 to 35 percent)	0.9		
Mahana silty clay loam (6 to 35 percent)	0.8		
Other soils[1]	0.9		
All Soils Total	100	PERLND Areas Total	88.0
[1] 'Other soils' are comprised of small areas of the following: Waipahu silty clay, Tropaquepts, Paaloa silty clay, Water > 40 acres, Honouliuli clay, Keaau clay, and Coral outcrop			



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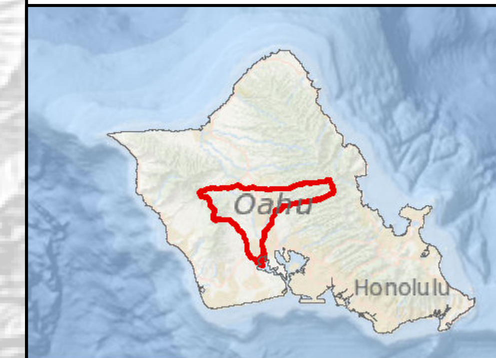

Legend

- USGS Gages
- Streams
- Roads (Major)
- HSPF Sub-Basins

Soils

- Koolau Mountain Soils
- Silty Clay Soils (< 30% Slope)
- Rock Valley Soils
- Silty Clay Soils (>=30% Slope)
- Waianae Mountain Soils

NOTE: Koolau Mountain Soils group is modeled as separate High and Low Runoff classes.

SCALE - 1:72,000

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Coordinate System: NAD 1983 HARN STATEPLANE HAWAII 3 FIPS 5103 FEET

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Central Oahu Watershed Study

Soils

FIGURE 7

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3.2 Subbasin Delineation

The 46.1 square mile watershed was subdivided into 55 subbasins ranging in size from 0.01 to 2.4 square miles. Each subbasin was delineated to a desired outlet location based on topographic contours and the City and County of Honolulu stormwater GIS inventory. Subbasin outlet locations were chosen at stormwater outfalls and established flow gaging locations, in addition to those as-needed based on predominant land uses, soil types, precipitation patterns, and/or land management practices within the land surface. Table 12 summarizes the basin areas and stream lengths for each tributary watershed.

Table 12: Areas and Stream Lengths for the Tributary Watersheds

Watershed	Tributary Streams	HSPF Model Subbasin No.	Area (sq mi)	Stream Length (mi)
Waikakalaua[1]	Waikakalaua	90a,90b,92a,92b,92c,94,95, 96, and 98	5.8	20.2
Kipapa	Kipapa	48,50,51,52,54,56,58,60,62, 63,64,66,68,70,72,74,76,78, 80,82,84,86, and 88	15.5	40.9
Upper Waikele	Upper Waikele	24,26,28,29,30,32,33,34, and 35	9.3	21.3
Lower Waikele	Lower Waikele	10,12,14,16,18,20, and 22	6.9	10.2
Waianae Range Tributaries	Ekahanui, Huliwai, Poliwai and Manuwaiahu Gulches	36,38,40,42,43,44, and 46	8.4	20.7
Total Watershed			46.1	113.2

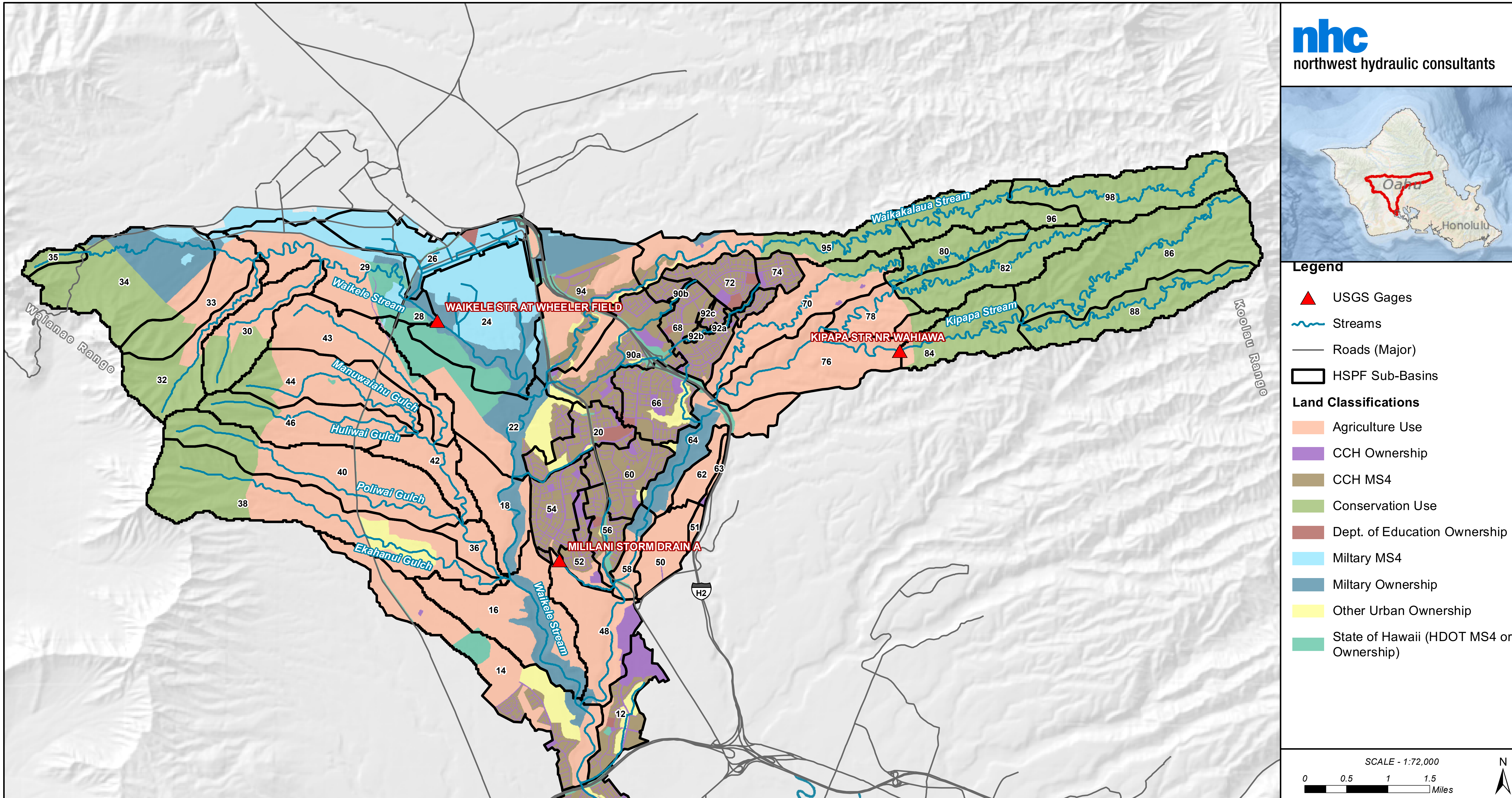
[1] Waikakalaua subbasins 90 (a, b and c) and 92 (a and b) were delineated as five separate polygons in the GIS but are only modeled as two (90 and 92) in HSPF.

3.2.1 Municipal Separate Storm Sewer System (MS4) Areas

In addition to hydrologic basin boundaries, the model has also been divided up into land classifications based on Municipal Separate Storm Sewer System (MS4) permit, land ownership, or land use designations. MS4 areas are those that drain to a regulated MS4. The ownership land classifications applies to areas that are owned by a MS4 entity; even if the area doesn't drain to their stormwater system. Examples of ownership areas include CCH parks, CCH right-of-way, and Military training or riparian areas that are under military ownership. Areas for each of the land classifications are summarized in Table 13 and are mapped in Figure 8.

Table 13: MS4 Land Classification Areas Within Waikele Watershed

MS4 and/or Ownership	Land Classification	Area ($miles^2$)
City and County of Honolulu (CCH)	Ownership	1.9
	MS4	4.6
Other Urban	Use	1.1
Military	Ownership	3.3
	MS4	2.5
State of Hawaii (HDOT and other)	Owned and MS4	1.8
Hawaii State Department of Education (DOE)	Owned	0.2
Agriculture	Use	17.8
Conservation Land	Use	12.9
Total Area		46.1



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Job: 21831 | Date: 04-Apr-2017

Central Oahu Watershed Study

Land Classifications (Including MS4s)

FIGURE 8

3.3 Stream (RCHRES) and Channel Geometry (FTABLE) Generation

Every subbasin in the Waikele Stream watershed was assigned a corresponding stream reach called a RCHRES in HSPF; the RCHRES IDs are identified in Figure 10. HSPF applies a simplified approach to hydraulic routing based on the equation of continuity and a calculation of reach outflows as a function (one-to-one relationship) with reach storage. This approach is also known as "hydrologic", "storage", or "reservoir" routing. For free flowing channel reaches, the outflow-storage relationship is often determined by Manning or another uniform flow relationship. The stage-storage-discharge relationship (FTABLE) must be entered into the model by the user. While simple backwater effects can be captured, any dynamic backwater situation that violates a fixed one-to-one relationship between reach outflow and reach storage cannot be accurately portrayed. Thus, the model cannot represent phenomena such as loop rating curves, flow reversals, tidal fluctuations, or other situations in which downstream water levels are poorly correlated with storage within the reach.

When simulating sediment transport with HSPF, the channel geometry defined by the FTABLE directly affects the stream velocity—the shear stress at the channel bed and, depending on the channel erosion parameters, also the deposition or scour of bed material. Ideally, measured cross-section geometry would be available to generate FTABLES for each reach of the HSPF model. Several different methods were used to calculate FTABLES for the HSPF model stream reaches. Of the 51 reaches included in the model, 42 are natural open-channel stream reaches, eight are closed conduit pipe networks, and one represents two large detention ponds.

Natural Open-Channel Stream Reach Geometry

Unfortunately, survey data do not currently exist for each of the 42 natural open-channel stream reaches. In lieu of measured data, the FTABLEs for those reaches were instead estimated following a method similar to that outlined in BASINS (EPA, 2007a and 2007b). A sketch from EPA (2007a) is included below as Figure 9, representing the basic features of the assumed floodplain geometry. The bankfull channel is represented as a trapezoid with width and depth estimated from basin area (Ames, 2009) and 1:1 (H:V) side slopes. At the top of the main channel bank, the first step in the floodplain is flat and assumed to be two times the width of the bankfull. At the outer edge of the first floodplain step, the floodplain slopes upward again at 1:1, side slopes to a depth of 2.5 times the bankfull depth. The upper edges of the floodplain then extend steeply upward at 0.5:1 side slopes. Each FTABLE is made up of four columns (Depth, Surface Area, Volume and Outflow) and rows defined at half-foot depth increments or greater. A tabulation of measured and estimated parameters for each RCHRES is presented below in Table 14.

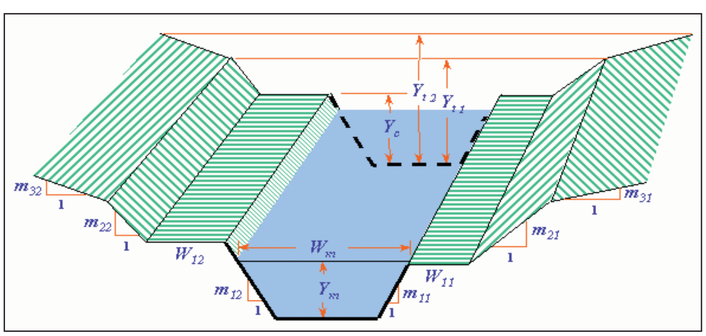


Figure 9: Natural Stream channel cross-section geometry (EPA, 2007b)

Table 14: Natural Stream Channel Geometry Parameters

RCHRES	Stream	Minimum - Maximum Elevation (feet)	Slope (ft/ft)	Length (miles)	Cumulative Drainage Area (miles^2)	Bankfull Width[1] (feet)	Bankfull Depth[1] (feet)
10	Waikele	11 - 37	0.006	0.89	46.19	74.7	14.5
12	Waikele	30 - 267	0.028	1.58	0.62	5.6	2.6
14	Waikele	27 - 81	0.009	1.2	45.16	73.7	14.3
16	Waikele	80 - 313	0.021	2.09	27.84	55.1	11.8
18	Waikele	297 - 468	0.02	1.63	17.91	42.3	9.9
20	Waikele	466 - 679	0.035	1.16	0.52	5.1	2.4
22	Waikele	463 - 577	0.013	1.62	16.67	40.5	9.6
24	Waikele	527 - 691	0.015	2.02	9.56	29.0	7.7
28	Waikele	691 - 935	0.011	4.31	6.92	23.9	6.8
30	Waikele	834 - 1802	0.079	2.31	0.90	7.0	3.0
32	Waikele	929 - 2261	0.097	2.6	0.85	6.8	2.9
33	Waikele	926 - 2870	0.018	0.56	2.83	14.0	4.7
34	Waikele	974 - 2843	0.100	2.12	2.04	11.4	1.4
35	Waikele	1375 - 2803	0.401	0.63	0.13	2.2	4.2
36	Huliwai	297 - 562	0.043	1.18	8.42	26.9	7.3
38	Huliwai	323 - 1889	0.061	4.88	2.38	12.6	4.4
40	Huliwai	529 - 2221	0.077	4.18	1.84	10.8	4.0
42	Poliwai	527 - 681	0.018	1.66	3.91	17.0	5.4
43	Poliwai	646 - 959	0.019	3.05	1.14	8.1	3.3
44	Poliwai	667 - 1614	0.064	2.82	1.14	8.1	3.3
46	Poliwai	670 - 2031	0.089	2.88	1.04	7.7	3.2
48	Kipapa	78 - 239	0.015	2	15.44	38.7	9.3
52	Kipapa	239 - 530	0.069	0.8	0.95	7.3	3.1
54	Kipapa	530 - 537	0.017	0.07	0.60	5.5	2.5
56	Kipapa	240 - 555	0.059	1.01	0.36	4.1	2.1
58	Kipapa	239 - 321	0.013	1.15	12.72	34.5	8.6
64	Kipapa	319 - 477	0.015	1.97	11.64	32.7	8.3
66	Kipapa	440 - 720	0.063	0.84	0.72	6.1	2.7
70	Kipapa	476 - 1064	0.024	4.56	1.87	10.9	4.0
76	Kipapa	469 - 707	0.014	3.12	7.55	25.2	7.0
78	Kipapa	582 - 858	0.025	2.13	2.00	11.4	4.1
80	Kipapa	858 - 1778	0.047	3.69	0.53	5.1	2.4
82	Kipapa	851 - 1961	0.041	5.14	1.02	7.6	3.1
84	Kipapa	706 - 977	0.019	2.67	4.13	17.6	5.5
86	Kipapa	969 - 2498	0.046	6.27	2.24	12.2	4.3
88	Kipapa	974 - 2480	0.056	5.09	1.01	7.6	3.1
90	Waikakalaua	552 - 879	0.022	2.77	1.15	8.1	3.3
92	Waikakalaua	679 - 973	0.023	2.41	0.07	1.5	1.1
94	Waikakalaua	548 -	0.004	2.49	4.70	19.0	5.8
95	Waikakalaua	- 1005	0.023	5.22	3.18	15.2	5.0
96	Waikakalaua	978 - 1215	0.016	2.76	2.05	11.5	4.2
98	Waikakalaua	1205 -2442	0.051	4.57	1.21	8.4	3.4

[1] Bankfull width values were calculated based on drainage area following relationship built into BASINS and were then exaggerated by a factor of 5 based on typical channel conditions observed on Oahu [Depth in meters = 5 x 0.13 x (Area in km)$^{0.4}$]. Both of the relationships used in BASINS can be found in Ames et al. (2009).

Closed Conduit Stormwater System Reach Geometry

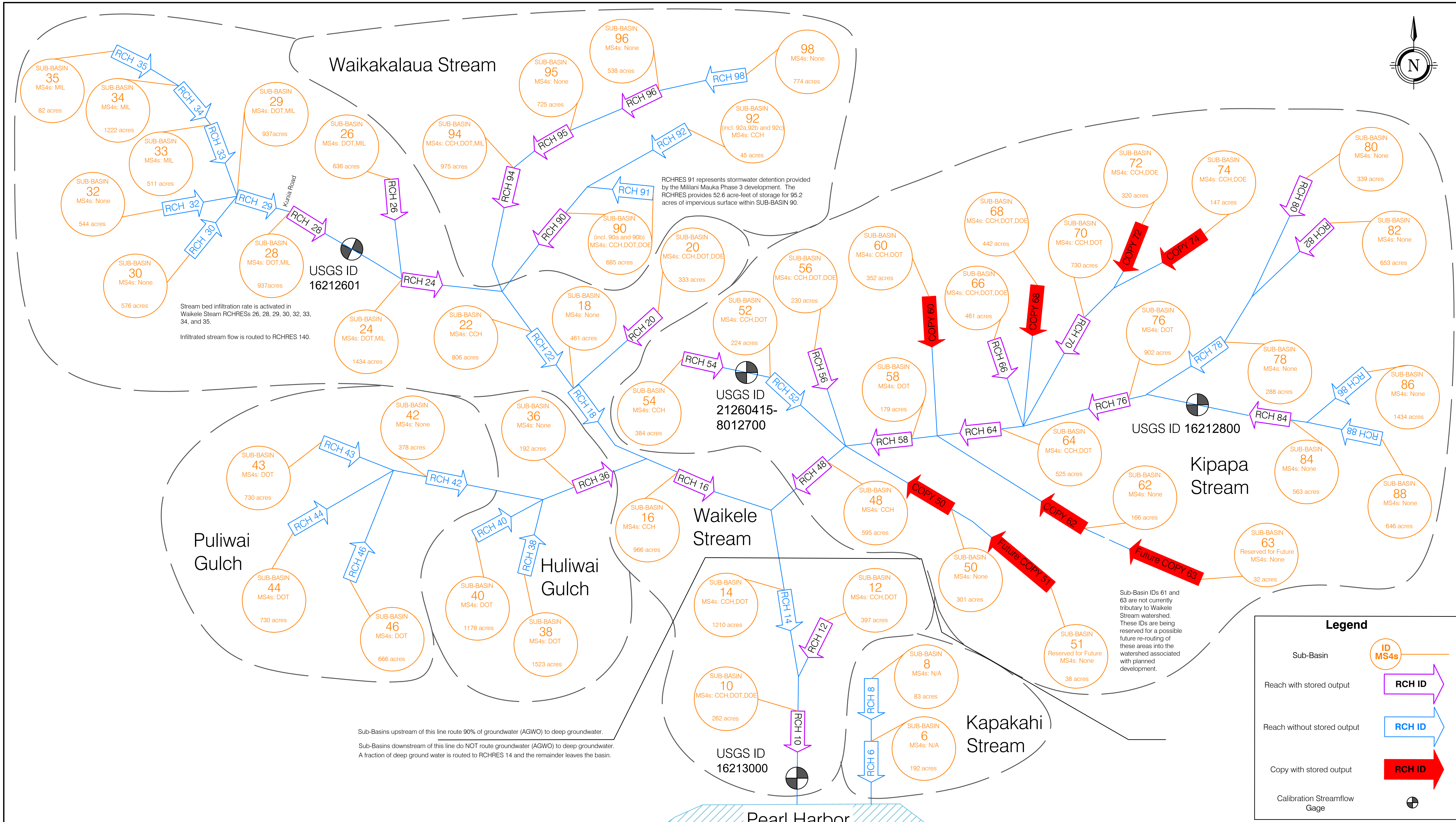
Reaches 52 (Mililani Storm Drain A), 56, 60, 66, 68, 72, and 74 were defined using pipe conduit length and diameter attributes from CCH's stormwater GIS database.

Reaches 29[3] (Kunia Road), 33 (Hauula Street), and 34 (open water crossing), all located in the Upper Waikele basin, are represented as open channels that are backwatered by culverts at road-crossings. The effect of backwater conditions during large storm events was identified during model calibration to very large storm events (e.g. December 2008). By adding these restrictions the model was better able to represent the storage in the conveyance system and replicate the timing of the event hydrograph. The Kunia road crossing opening dimensions were available in the CCH's stormwater GIS database, but reach 33 and 34 are located on US Army property and are not included in CCH's data. The geometry of these two crossings were estimated from aerial imagery.

Detention Pond Geometry for Mililani Mauka Phase 3 Development

Of the 11 known and documented stormwater facilities within the study area, only the two at the Mililani Mauka Phase 3 development provide more than five acre-feet of storage. Together, the Mililani Mauka Phase 3 development's North and South Gully System detention ponds provide 52.6 acre-feet of stormwater detention to a portion of sub-basin 90a. These two facilities were represented as a single facility in HSPF, RCHRES 91. The stage-volume-discharge relationship for the combined facilities were defined from tabulations in design documentation reports. Due to a lack of resources and documentation, the remaining nine facilities which are smaller than five acre-feet were not explicitly represented in the model. Due to the relatively small size of these facilities, they were considered to have a minimal net effect on stream flow and watershed-wide water quality.

[3] There is no sub-basin 29. Sub-basin 28 includes two separate routing reaches, divided at Kunia Road. Routing reach 28, which extends from Kunia Road to the USGS gage Waikele Stream at Wheeler, receives flows from reaches 26 and 29.



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Drft:	DLS
Chkd:	
Date:	18Sep17

Waikele Stream
HSPF Model Schematic

FIGURE 10

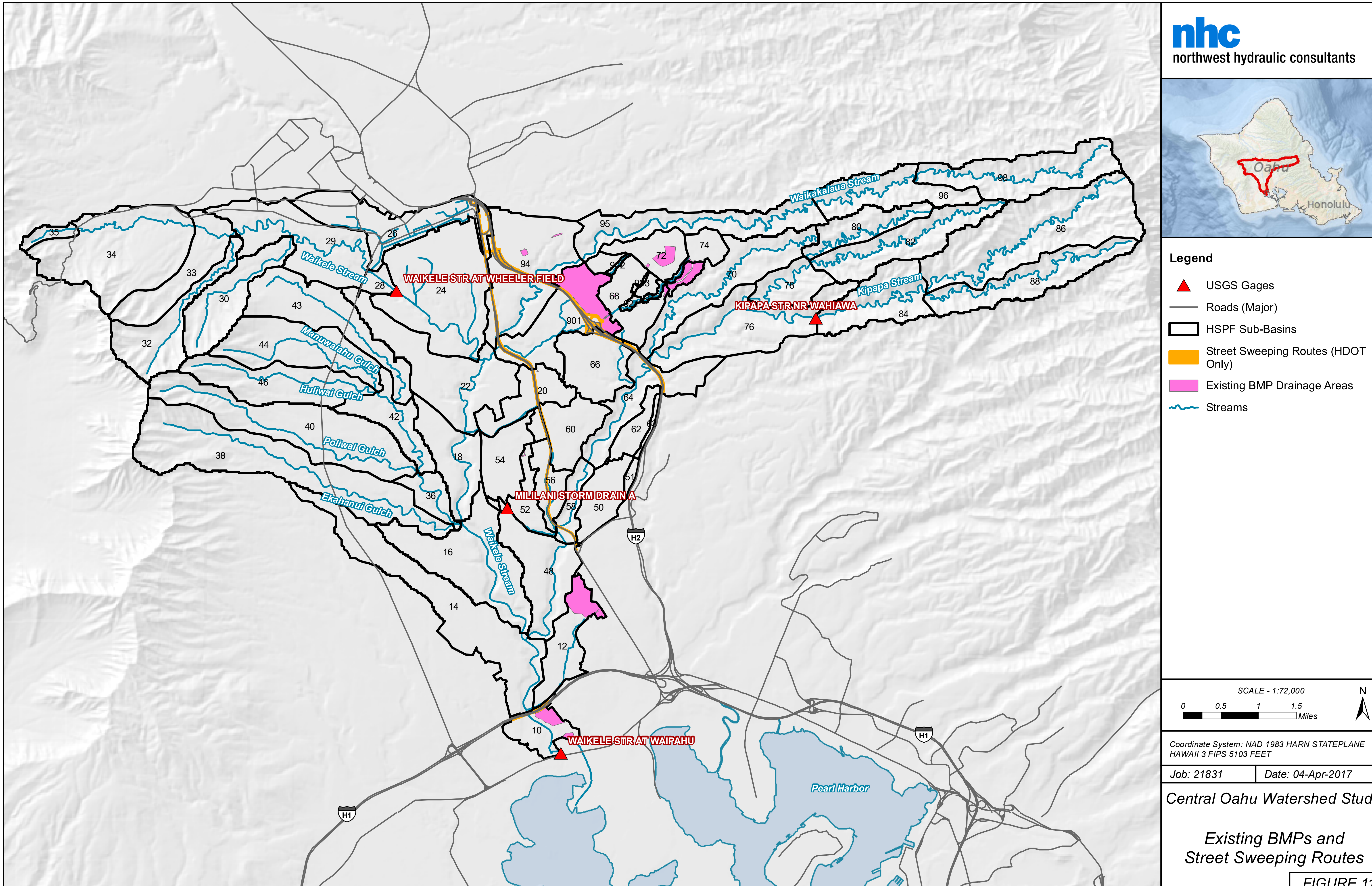
3.4 Water Management

Waiahole Ditch conveys water collected on the windward side of Oahu across the Waikele Stream basin. No known uses of that water are believed to be active within the watershed. Based on this information, Waiahole Ditch was excluded from the HSPF model.

Other water uses in the basin, such as irrigation and domestic use, are expected to have relatively small effects on suspended sediment transport in the basin and were also ignored for the purposes of this study.

3.5 Existing Stormwater Best Management Practices (BMPs)

The two primary actions that are currently implemented in the basin to control sediment sources in the watershed are permanent BMPs and street sweeping (Figure 11).



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Central Oahu Watershed Study

Existing BMPs and Street Sweeping Routes

FIGURE 11

Permanent BMPs

Table 15 includes a listing of all of the existing permanent BMPs known to be in the Waikele Watershed and included in the CCH GIS stormwater inventory. Design calculations were not available for existing facilities, so for modeling purposes, the area treated by each BMP was estimated based on the area of the parcel(s) in which the BMP is located.

Table 15: Existing Permanent BMPs

Location Name or ID	Treatment Area (Acres)	Device	Count
37786	7.5	Hydrodynamic Separator	1
51875	7.5	Infiltration Device	2
55325	1.1	Swale	1
56544	7.4	Swale	1
59184	0.17	Hydrodynamic Separator	5
59184	0.17	Inlet Filter	10
59853	0.23	Swale	1
59860	0.05	Swale	1
59860	3.8	Swale	1
60587	35.3	Hydrodynamic Separator	1
60587	35.3	Inlet Filter	12
The Renaissance	92.5	Detention	1
Central Oahu Regional Park	16.2	Detention	1
Mililani Mauka MF107A,B,C	1.2	Detention	1
Castle & Cooke Self Storage	52.6	Detention	1
Mililani Mauka Unit 123 124 125	193.1	Detention	1
Mililani Mauka PH3 North and South Gully	59.3	Detention	2
Mililani Mauka MF109	7.5	Detention	1

The amount of sediment removed by each BMP is assigned to the HSPF model via the Best Management Practices (BMPrac) module. The module allows the user to assign a pollutant removal efficiency to each BMPrac element that sediment load is then removed from the runoff generated from the tributary area of land surface (PERLND or IMPLND). The removal efficiency for BMPs were based on generic removal rates based on literature values. All literature and/or manufacturer cited removal rates were reduced by 30 percent to account for overflows that bypass the treatment device. Most BMPs in Hawaii are designed to treat runoff at a rate equivalent to an inflow rate generated by a 24-hour storm with one-inch of rainfall depth (Department of Planning and Permitting, 2002). Based on NHC's review of local rainfall data, approximately 30 percent of the long-term rainfall volume exceeds this depth threshold.

The Mililani Mauka PH3 North and South Gully detention ponds are represented as both an FTABLE routing reach and a BMPrac reduction factor. Sand settles in the FTABLE but clay and silt do not. To avoid double counting the removal of sand, the BMPrac for this BMP only provides removal of silt and clay.

Table 16: Literature TSS Removal Rates by BMP Type

Total Suspended Solids	Literature Reduction Factor (% removal)	Applied Reduction Factor (% removal) [5]
Detention[1]	66.0	46.2
Wet Ponds[1]	76.0	53.2
Stormwater Wetlands[1]	62.0	43.4
Biofiltration[3]	86.0	60.2
Bioretention[1]	74.0	51.8
Inlet Filter[2]	83.0	58.1
Infiltration[3]	90.0	63.0
Vegetated Swale[3]	81.0	56.7
Hydrodynamic Separator[4]	60.0	42.0

[1] International BMP Database (2014)
[2] Typical CIWMB; ConTech Filtera; FlexStorm
[3] Center for Watershed Protection (2007)
[4] Listed 60% removal is average of Vortech literature listed:
80% removal at 13 GPM/sf, mean particle range 38 to 75 microns
40% removal at 5 to 10 GPM/sf, mean particle size of 25 microns
[5] Based on designs capturing 24-hour rainfall depth less than 1 inch. Analysis indicates 30% of rainfall exceeds this amount, thus only 70% of inflow volume is treated.

Street Sweeping

CCH does not currently have formal street sweeping activities in the Waikele Watershed, but the Hawaii Department of Transportation (HDOT) does perform street sweeping within the basin. HDOT-Highways is obligated to perform street sweeping under their Consent Decree.

> *"Street sweeping schedules are currently completed in accordance with the minimum requirements specified in the Consent Decree. Highway segment sweeping schedules are divided into categories "A" and "B" based upon material accumulation rates and the potential threat of discharge affecting water quality. Category "A" segments are considered high priority and are swept at least once every five weeks. Category "B" segments are considered low priority and are swept once every fifteen weeks."* HDOT (2015)

All of the state highways within the study area are identified as Category "A" segments with five-week sweeping frequencies. For model calibration purposes it was assumed that all roadways in state ownership are swept with a frequency of approximately once per month. These include the H-1 and H-2 freeways and Kamehameha Highway (State Route 99).

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The street sweeping removal rate is assigned to HSPF as a percent of the sediment present per day. This rate was determined using the following equation.

$R = P * (E/D)$
where:

R = sediment removal rate per day
P = fraction of impervious area swept
E = removal per sweeping (%/100)
D = frequency of cleaning (days)

At a 30 day sweeping interval, 80% removal per sweeping, and full coverage of areas classified as swept, this equation equates to 2.6% removed per day. Since the mass of sediment stored on impervious surfaces varies as a function of precipitation and runoff, the mass or volume of sediment actually removed also varies temporally and spatially throughout the basin. For example, in the Pearl Harbor rainfall region, where several of the HDOT highways are, the modeled simulated a total removal of 0.106 tons/acre/year (214 lbs/acre/year). This corresponds to a 22% reduction in the total annual pollutant load for swept impervious surfaces relative to non-swept impervious surfaces. Ideally the removal rate currently being obtained by HDOT street sweeping operations could be confirmed and/or refined to match sweeper yield data collected from HDOT sweepers operating in the basin. Similarly, if street sweeping is utilized as a BMP for DFM-SWQ's roadways in the future, a rate consistent with monitored sediment removal rates in the basin or in similar basins on Oahu should also be used.

4 CALIBRATION TO OBSERVED FLOW AND SEDIMENT MEASUREMENTS

Calibration is the process of adjusting model parameter values with the goal of achieving an acceptable level of agreement with observed data. Calibration of the HSPF model was performed in three sequential phases: hydrology, sediment, and water quality (nutrients). The ability to achieve a good water quality calibration is dependent on the sediment calibration, and similarly, the sediment calibration is dependent on the hydrology calibration.

A simulation period of October 1997 through September 2011 was selected for the HSPF model calibration[4]. The beginning date of October 1997 corresponds to the beginning of the first water year in which the Poamoho No. 1 and 2 rain gages were reporting sub-daily rainfall. The analysis period could be extended to an earlier date, but model output in precipitation Zones 1 and 6 could not be generated using a rain gage suitable for generation of sub-daily output. The ending date of September 2011 was selected to include data from the USGS and USACE monitoring programs, which both ended in 2012. The simulation period is referred to as Water Years 1998 through 2012 throughout this report.

Quality Objectives for Modeling

The intended use of the model is a determining factor in the level of Quality Assurance (QA) needed, as it indicates the seriousness of potential consequences or impacts that might occur due to quality problems with the model or the data used with it. The objective of modeling for this project was to develop a HSPF water discharge and fine sediment water quality model to conduct planning level analyses of management practices, as well as future support for compliance with TMDLs. Ultimately, the goal is to preserve or improve water quality and beneficial uses in Waikele Stream and Pearl Harbor. Aspects of the model that have achieved a good fit with high quality observed data can generally assume a strong role in evaluating management decisions that result from impact analysis. Conversely, where a model achieves only a fair or poor fit, it should have a much less prominent role in the overall weight-of-evidence evaluation of management options (Donigian, 2002). The calibration used here utilizes a weight-of-evidence approach by considering a combination of qualitative and quantitative measures of calibration including:

- Visual evaluation of graphical time-series or scatter plots of observed flow, loads or concentrations,
- Tabulations of measured and predicted values, and
- Error statistics.

Not all data utilized for this effort are of the same level of accuracy. Some discussion of this is included in the calibration discussions that follow.

[4] The model was also run for a short simulation period known as the model warm up, from January 1, 1989 to October 1, 1997. The warm up is necessary to establish the soil moisture condition at the beginning of the calibration period.

4.1 Observed Calibration Data

Historical stage, stream flow, suspended sediment (SSC or TSS), nitrogen, and/or phosphorus data have been collected at 14 unique locations within the study area during various time periods. These locations are mapped in Figure 2 (presented in Section 1.5) and tabulated within the following discussions.

USGS Stream Flow Data

Table 17 presents a tabulation of data availability at each of the seven USGS stream gaging sites in the basin, including the four that were operated by the USGS under a joint funding agreement between the USGS and the City and County of Honolulu between 2007 and 2011. The available record includes the December 2008 event, which produced the largest flow ever recorded at the Waikele gage. The estimated peak flow reached 22,500 cfs; the previous historic peak on record was 13,600 cfs (on November 11, 1954). As of March 2017, the only USGS gage that remains active in the basin is Waikele Stream at Waipahu.

Revision to Published USGS Mililani Storm Drain A Flow Record

Initial comparisons of the HSPF model's simulated discharge and sediment load to the USGS's observed discharge and load at the Mililani Storm Drain A (aka Mililani Storm Drain) for storms during the 2008 - 2010 USGS study period indicated that the model over-estimated storm discharge and sediment loads by more than a factor of 4 or more. Discussions with the USGS concerning this anomaly were initiated in 2010 with follow-ups early in 2016. As a result of these discussions, two significant sources of these large discrepancies were discovered, one associated with excessive rainfall being applied to the Miliani area in the HSPF model, and the other associated with errors in the USGS rating curve that greatly underestimated discharge—especially at higher stages. When the existence of a rain record from a local Mililani Town co-op rain gage was identified in early 2016, it was discovered that in some large storms the Mililani storm drain basin received about half the amount of rainfall recorded at a rain gage at Wheeler Air Force base only a few miles away. For example, during the flood of record storm event on December 11, 2008, 10.6 inches was recorded at Wheeler, while only 4.3 inches is estimated to have fallen in Mililani Town (see Figure 4). Substitution of the local rain record into the model lowered the simulated runoff and sediment load by a factor of two relative to that simulated using the NEXRAD data; however, there was still a very large discrepancy remaining with the USGS record for this event. It was concluded that the source of this remaining discrepancy was the USGS record itself based on hydrologic mass balance for the December 11, 2008 event. The highly urban area that contributes runoff to the Mililani Storm drain and USGS gaging site has a total impervious area of 263 acres. Even if it is assumed that only 50 percent of the roofs, roads, driveways, and sidewalks contributed runoff during this storm, this would result in a daily volume of 43-ac-ft, or more than four times the 9.1 ac-ft reported by the USGS. The source of the apparent under-reporting of runoff appears to have been an erroneous stage-discharge rating curve that was constructed based on backwater modeling by the USGS (personal communication, Ron Rickman, USGS, January 15, 2016). The USGS gaging site employed a low weir across the rectangular storm drain channel to force critical depth and provide more accurate measurements of small discharges. An error in the backwater model was clear when NHC examined the water surface profiles provided by the USGS associated with large discharges. These indicated that the very low weir was continuing to act as a control at water depths that certainly would have drowned out any effect of the weir on discharges in the channel. NHC recomputed the stage discharge curve using the actual weir geometry to arrive at a more correct record of observed discharges and storm volumes that made sense when compared with the corrected rainfall from the Mililani Town rain gage, as well as the known amount of impervious area contributing to the storm drain.

Since the USGS derived suspended sediment loads by combining observed sediment concentrations with observed discharges, their sediment loads were also greatly under-estimated for storm events that produced larger stages and discharges. This load difference—which was not fully resolved until February 2016—is not reflected in the January 2016 version of NHC's geomorphic assessment (Appendix A), but it is reflected in Section 4.3 of this text.

The combined application of the local rainfall record to the model (and the correction of USGS discharge and sediment data) resulted in vastly improved matches between the calibrated HSPF model and the corrected observations of storm discharge and sediment load at the Mililani Storm Drain. These are discussed in more detail in Section 4.2.

US Army Stream Flow Data

Table 18 presents a tabulation of data availability at each of the four US Army stream gaging sites that were operated on Upper Waikele Stream (aka Waikele Gulch) between 2008 and 2011. These data were obtained from Tables 1, 8, B1, B2, B3, and B4 of the USACE (2015) report which was released to the Waikele Stream TMDL group in early 2016. USACE (2015) provides the following description of the four gage locations and the nature of runoff reaching these sites:

> *Surface water discharge is an infrequent event in the [upper] Waikele watershed. ... Flow very rarely occurs at Stations SW-5 and SW-6 due to infiltration and stream bed losses. In contrast, for the gaging locations SW-11, SW-12, and the USGS gage, many more storms resulted in flow due to the impermeable areas on Schofield Barracks and Wheeler Army Airfield with storm drains. Even in the lower areas of the watershed, there is wide variability between SW-11, SW-12, and the USGS [Waikele Stream at Wheeler] gages as a result of local rainfall variations. In addition, flow measured at SW-11 or the USGS gage will infiltrate into the Waikele Stream riverbed before reaching SW-12.*

Table 17: Available USGS Flow and Stage Data Locations

Stream Name (USGS Station ID)	Drainage Area[2] (sq. mi.)	Period of Daily Flow Record	Period of Sub-Daily Flow Record	Mean Annual Discharge (cfs)	Peak Flow of Record (cfs)	Period of Peak Flow Record	Date of Peak of Record
Waikele Stream at Waipahu[1] (16213000)	46.2	1953 to current	Oct. 1, 1986 to current	39.7	22,600[3]	1952 to current	Dec. 11, 2008
Waikele Gulch at Wheeler Field[1] (16212601)	6.9	2008 and 2009	Sept. 28, 2007 to Oct. 3, 2010	0.6	1,810	1958 to 2010	Mar. 5, 1958
Kipapa Stream near Waipahu (16212900)	15.5	1968 only	N/A	15.6	N/A	N/A	N/A
Kipapa Stream Near Wahiawa[1] (16212800)	4.1	1957 to 2004 and 2008 to 2010	Oct. 1, 1990 to Sept. 30, 2004 and Oct. 1, 2007 to Oct. 12, 2011	10.5	6,370	1957 to 2004 plus 2008 - 2010	Mar. 21, 1991
Waikakalaua Stream near Wahiawa (16212700)	5.9	N/A	N/A	N/A	4,820	1958 to 2011	Apr. 15, 1963
Huliwai Gulch (16212750)	0.9	N/A	N/A	N/A	500	1980 to 2004	Jan. 6, 1982
Mililani Storm Drain A[1] (21260415-8012700)	0.6	N/A	N/A	N/A	205	2008	Nov. 4, 2008

[1] Gage operated under joint operating agreement between the City and County of Honolulu and USGS[2] Drainage areas shown correspond to those in HSPF model and differ slightly from those reported by the USGS[3] Peak flow as per USGS (2008)

Table 18: US Army Corps of Engineers Flow Measurement Locations

Site Name (USACE Station ID)	Drainage Area[2] (sq. mi.)	Period of Reported Storm Volumes	Number of Reported Storm Volumes	Number of Storms with Measured Flow	Maximum Reported Storm Volume (acre-ft)	Date of Maximum Reported Storm Volume	Number of Reported Instantaneous Discharge Values[1]
SW-6	0.13	Feb. 15, 2008 to Jun. 4, 2011	44	9	166.1	Jan. 2011	38
SW-5	2.0	Feb. 15, 2008 to Jan. 17, 2009	22	1	64.7	Dec. 2008	4
SW-11	6.9	Feb. 15, 2008 to Jun. 4, 2011	44	29	1754.2	Dec. 2008	160
SW-12	9.3	Feb. 15, 2008 to Jun. 4, 2011	43	27	3301.9	Dec. 2008	110

[1] Instantaneous discharge values are only reported for time intervals when water quality samples were collected and do not reflect the event "peak".

Summary of Sediment and Nutrient Data

Table 19 (on next page) summarizes the periods of record for the available Waikele Watershed water quality data. There are nine sites with some suspended sediment (TSS), total nitrogen (TN) or total phosphorus (TP) data. Most are instantaneous (Inst.) grab samples (i.e., they do not capture complete storm events), with the exception of data collected between 1967 and 1993, a limited period at one station in 2002, and the data collected as part of the USGS-DFM-SWQ joint operating agreement. Data collected by the USGS at Waikele Stream at Waipahu and Kipapa Stream near Wahiawa between 1967 and 1993 are available as mean daily loads and were presumably collected as sequential samples, but no documentation of the method was available. The DOH monitoring performed by Oceanit in 2002 included grab sampling at sites throughout the study area. While the program was only continued for a short period, the data set is useful in analyzing the spatial distribution of sediment and nutrient loads within the watershed. Data currently being collected by the USGS includes sequential samples of TSS but no TN or TP. During the 2007 through 2011 USGS monitoring program, there were several moderate sized storm events that were sampled (e.g. November 4, 2007). Unfortunately, the event of record that occurred on December 11, 2008 washed out the instrumentation at Waipahu, and thus, no water quality data were collected for the storm event at that site. The sensors in Waikele Stream at Wheeler Field and Kipapa Stream were initially thought to been damaged, but data were later released by the USGS.

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Table 19: Available Suspended Sediment and Nutrient Data

Location-Name	Site ID (USGS, DOH Oceanit, or USACE)	HSPF Reach	Suspended Sediment (SSC or TSS)	Total Nitrogen (TN) [3]	Total Phosphorus (TP)
Waikele Stream at Waipahu[1]	16213000 / STA 1	10	Daily (1972-1993), Periods of Seq. (2002), Inst. (2003-2004), Daily/Periods of Seq. (2007-2010)	Inst. (1973-2001), Periods of Seq. (2002), Inst. (2003 -2004)	Inst. (1973-2001), Periods of Seq. (2002), Inst. (2003-2004)
Waikele Stream above H-1 Freeway near Waipahu	21240215-8010501 / NA	10	Inst. (2000–2001)	Inst. (2000 – 2001)	Inst. (2000–2001)
Waikele Stream at Wheeler Field[1]	16212601 / NA	28	Daily/Periods of Seq. (2007-2010)	NA	NA
Waikakalaua Stream near Wahiawa	16212700 / STA 6	94 / 90[2]	Inst. (1999-2001, 2002)	Inst. (1999 - 2001, 2002)	Inst. (1999 - 2001, 2002)
Kipapa Stream at Waipahu	16212900 / STA 4	16	Inst. (1967-1968, 2002)	Inst. (2002)	Inst. (2002)
Kipapa Stream near Wahiawa[1]	16212800 / STA 7	84	Daily (1968-1982), Inst. (2002), Daily/Periods of Seq. (2007–2010)	Inst. (2002)	Inst. (1973 - 1977), Inst. (2002)
Mililani Storm Drain A at Mililani[1]	21260415-8012700 / NA	54	Periods of Seq. (2007–2010)	Inst. (1980 - 1982)	Inst. (1980 - 1982)
Upper Waikakalaua (upstream of Subdivision)	NA / STA 8	94	Inst. (2002)	Inst. (2002)	Inst. (2002)
Waikele Upstream of Kipapa Confluence	NA / STA 3	48	Inst. (2002)	Inst. (2002)	Inst. (2002)
Wheeler Near Stables	NA / STA 5A	24	Inst. (2002)	Inst. (2002)	Inst. (2002)
Waikele Stream, Training Area	SW-5	34	Inst. (2008)	Inst. (2008)	Inst. (2008)
Waikele Stream, Waianae Upland	SW-6	35	Inst. (2008 – 2011)	Inst. (2008 – 2011)	Inst. (2008 – 2011)
Waikele Stream, Below Wheeler Airfield	SW-11	28	Inst. (2008 – 2011)	Inst. (2008 – 2011)	Inst. (2008 – 2011)
Waikele Stream, Above Confluence with Waikakalaua	SW-12	24	Inst. (2008 – 2011)	Inst. (2008 – 2011)	Inst. (2008 – 2011)

[1]Site currently operated under joint operating agreement between USGS and DFM-SWQ
[2]DOH Oceanit study location STA 6 is located below HSPF Reach 94 and 90 but above 22, reflects combined conditions from RCHRESs 90 and 94.
[3]Periods with Total Nitrogen Data typically also include Nitrate/Nitrate Samples but that data has been omitted from the table for brevity.[4]1980–1982 samples for Mililani Storm Drain B have been omitted from table.

4.2 HSPF Stream Flow Calibration

The hydrologic calibration of the Waikele Stream HSPF model was performed by setting an initial set of model soil parameters and modifying them to improve the match between simulated stream flow and observed stream flow at four primary calibration locations and four secondary locations. The primary locations include four USGS gages: Kipapa Stream at Wahiawa, Waikele Stream at Wheeler, Millilani Storm Drain A, and Waikele Stream at Waipahu. The secondary locations include three US Army monitoring locations (SW-5, SW-6, SW-11, and SW-12) that have smaller sample sizes and less information available about the monitoring program and QA/QC procedures. Calibration was only possible for periods with sufficient contemporaneous meteorological data that is causative of the observed flows. As discussed earlier, NEXRAD radar data was added to the available Waikele Stream watershed rain gage data to improve spatial distribution of rainfall applied to the model for calibration of selected large storms. Two different time scales were used to judge the quality of the Waikele Stream hydrology calibration: 1) matching the water balance of monthly average discharge over many water years, and 2) matching individual event hydrographs at an hourly time scale. The monthly time scale comparison was used to inform adjustments to the balance between runoff, evaporation, infiltration and deep groundwater recharge. After an acceptable monthly time scale calibration was achieved, individual storm hydrograph comparisons were then used to inform adjustments to the fraction and timing of runoff that responds as surface or shallow groundwater flow—known as interflow. These adjustments control the magnitude and shape of individual storm hydrographs. The range of calibrated PERLND parameters are shown in Table 20 and a discussion of the process that arrived at those values follows.

Table 20: Calibrated PERLND Hydrology Parameter Values and Sources

PARM2 and PARM3		PARM4 and STATE1	
Name	**Value**	**Name**	**Value**
FOREST	Not used	CEPSC	0.05 to 0.2
LZSN	1 to 12	UZSN	0.01 to 2.3
INFILT	0.05 to 4	NSUR	0.35
LSUR	100 to 300	INTFW	0.5 to 4
SLSUR	0.04 to 0.4	IRC	0.02 to 0.35
KVARY	0.00	LZETP	0.4 to 0.9
AGWRC	0.900 or 0.999	CEPS	0.00
PETMAX	Not used	SURS	0.0
PETMIN	Not used	UZS	Varies
INFEXP	2.0	IFWS	Varies
INFILD	1.0 to 2.0	LZS	Varies
DEEPFR	0.4 or 0.5	AGWS	Varies
BASETP	0.01	GWVS	Varies
AGWETP	0.00		
PERLND hydrology parameters listed in this table are defined in the HSPF User's Manual (Bicknell et. al, 2014) sections PWAT-PARM2, PWAT-PARM3, PWAT-PARM4, and PWAT-STATE1.			

Inspection of monthly average stream flows at all of these locations clearly indicates that a majority of precipitation volume in the study area does not manifest itself as streamflow at the downstream stream gage. Rather, this flow volume must instead reflect one or more of the following mechanisms: a higher evapotranspiration rate, net change inbasin storage, and/or a flow diversion or infiltration that does not resurface upstream of the stream gage. Infiltration that does not emerge upstream of the gage is the most likely mechanism accounting for low stream flow volumes because the other mechanisms are known to be absent from the basin or because they could not reduce stream flow volumes to the extent observed. Within HSPF, infiltrated runoff can be prevented from reaching the receiving stream by one of two typical methods: 1) by using the DEEPFR parameter to send a fraction of groundwater (AGWO) out of the watershed or 2) by specifying two outlets from each sub-basin, one that routes a fraction of groundwater (AGWO) to deep groundwater storage, and another that sends the remainder to the downstream stream receiving reach. The Waikele Stream HSPF model primarily used the second option, configured using two outlets from each sub-basin, routing to deep groundwater storage. A fraction of the total deep groundwater flow is assumed to return to Waikele Stream in Reach 14, near its confluence with Kipapa Stream, while the remainder is assumed to exit the watershed (either to the ocean or an adjacent basin). The Kipapa confluence was selected because the water level of the Central Oahu basal aquifer is at an approximate elevation of about 25 feet above sea level[5], an elevation that corresponds with the channel elevation of Waikele Stream at the confluence with Kipapa Stream. In addition to routing to two outlets, DEEPFR was also used to increase groundwater losses from Koolau and Waianae Mountain Soils by an additional 50%.

In addition to adjustment of the fraction of groundwater routed downstream or out of the system, there are several PERLND parameters that also play an important role in determining if water is infiltrated to groundwater or remains available for surface or interflow runoff. The two most important being INFILT (characteristic infiltration rate for a given PERLND) and LZSN (Lower Zone Nominal Storage). The LZSN parameter values were estimated from the SSURGO soils database and were not varied during calibration. The INFILT parameter, on the other hand, was varied along with the fraction of groundwater routed directly to the stream system, out of the watershed, or to the downstream confluence of Kipapa and Waikele stream. Due to the relatively small fraction of groundwater returning to the stream, the model was generally insensitive to AGWRC (Base Groundwater Recession), KVARY (Variable Groundwater Recession), and AGWS (Initial Active Groundwater Storage). During calibration, AGWS was not varied, KVARY was set to zero, and groundwater response was refined by varying AGWRC. Flow not sent to groundwater is partitioned between surface (SURO) and interflow (IFWO) runoff with the INTFW (Interflow Inflow Parameter) and the recession rate of interflow is controlled with the IRC (Interflow Recession Parameter).

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[5] 25 to 30 feet (Mink, 1962; Hirashima, 1971; vertical datum not referenced). A time-series of deep monitoring well data by the Honolulu Board of Water Supply at Waipahu (1986 to 2009) and Waipio Mauka (2004 to 2009) suggest a similar range and provide more detail on water surface elevations observed in the aquifer.

4.2.1 Observations from Specific Flow Gages

Observed flow records at the Kipapa Stream at the Wahiawa gage show very short but intense storm responses to small bursts of precipitation that are similar to the response of impervious surface, even though C-CAP land cover in the area is over 99.5 percent forest and scrub-shrub. Furthermore, over extended periods of months or years, a large fraction of the difference between rainfall and evapotranspiration over the drainage area is not registered as stream flow at the Kipapa gage. It was hypothesized that these two apparently conflicting trends—relatively small, sharply rising hydrographs, and apparently high losses of infiltrated groundwater—could be explained by the presence of two types of soils within the Kipapa subbasin: a smaller fraction of the basin with low infiltration rates and rapid runoff response, and the remainder of the basin with high infiltration rates, low runoff, and high loss of groundwater. During calibration, it was found that the observed stream flow records were well matched if 36 percent of the Kipapa watershed PERLND areas were modeled as a high runoff soil and the remainder as low runoff. The available SSURGO soil GIS data does not clearly indicate where these high and low regions might be located within the subbasin, nor does the SSURGO database include a detailed description of the rough mountainous land soil class, which covers 89 percent of the Kipapa subbasin. Wentworth 1947 and White 1949 characterize Koolau Range soils as having rock outcrops and other broken rock features. Feral pig activity in the mountainous areas is also known to create compacted trails in the vicinity of streams. The precise nature of the high runoff soil is not known, but it is clear that there is spatial variability in soil thickness and that some high-runoff areas in the subbasin are directly connected to Kipapa Stream. In order to achieve the required 36 percent of high runoff soil, 30 percent of the rough mountainous land soil, along with all of the non-rough mountainous land soils (all silty-clays) in the Kipapa USGS gage tributary area were assigned lower INFILT (i.e. high runoff) rates, while the remaining rough mountainous land soil was assigned a high INFILT rate.

Figure 12: View of erosion by surface runoff from bedrock exposure at lookout in Kolekole Pass

On the west side of the study area, opposite from the Kipapa Stream flow gage, is the USGS Waikele Stream at Wheeler gage, which drains the east-facing slopes of the Waianae range, the urbanized Schofield Barracks, and Wheeler AAF military installations. The comparison of simulated and observed flow data for the Wheeler flow gage and the four USACE gages (SW-5, SW-6, SW11, and SW-12) provided both similarities and differences relative to the Kipapa gage record. In general, the gage records show little to no runoff in these reaches during small to medium storm events. This is likely partly reflective of the lower precipitation of the Waianae range slopes relative to the Koolau, but even observed rainfall did not produce storm peaks at the gage that one would expect given the amount of impervious surface in the Upper Waikele Basin. Descriptions of the urban stormwater system do not indicate that there are major infiltration facilities that could retain and infiltrate flows, but USACE (2015) and NHC's site inspection both made observations that indicate infiltration is occurring in the channel bed in this reach. This behavior is reflected in the HSPF model in two ways: 1) the bed area of HSPF RCHRESs 26, 28, 29, 30, 32, 33, 34, and 35 were allowed to infiltrate (to varying degrees depending on channel bed type), and 2) the effective impervious area was reduced (see Table 10 in Section 3.1.2). The addition of channel infiltration results in drying up streamflow for the smallest events, however the impact of channel infiltration on larger storms is relatively small. Reducing effective impervious area has a similar effect as channel infiltration – more significant flow reductions in smaller events and less significant reductions in very large events. One additional difference in this basin was noted in the SW-6 gage record. This relatively small 0.13 square mile basin reported extremely high discharge rates exceeding 600 cfs, while there is generally very little runoff in these basins. The HSPF model could not replicate the magnitude of these observed peak flows, but the observations do justify using a set of soil parameters with even lower infiltration rates than those used for the high runoff Koolau soils.

A limited amount of daily flow data was collected by the USGS between 1967 and 1968 on Kipapa Stream just upstream of the confluence with Waikele Stream (Station 16212900). The model was not formally calibrated to the data at this location; however, the data were used to identify that the lower reach of Kipapa Stream does go dry annually at times when the upstream Kipapa Stream gage location does not. As a result of observing this flow losing behavior, bed infiltration was also activated in HSPF RCHRESs 58 and 64 on the lower mainstem of Kipapa Stream using a similar method as that described for Upper Waikele Stream.

The one USGS gage in the watershed that is positioned in an exclusively urbanized subbasin is Millilani Storm Drain. This gage, discussed previously in Section 4.1, is completely developed with predominantly medium density residential development. This basin was used to calibrate runoff from all residential land uses. Based on the adjusted USGS flow record, there is very little runoff from grass areas in the basin. This finding is consistent with observations by others regarding soils in the region. As stated previously in section 3.1.3, Mink and Lau (2006) describe the Wahiawa series as being as permeable as sand.

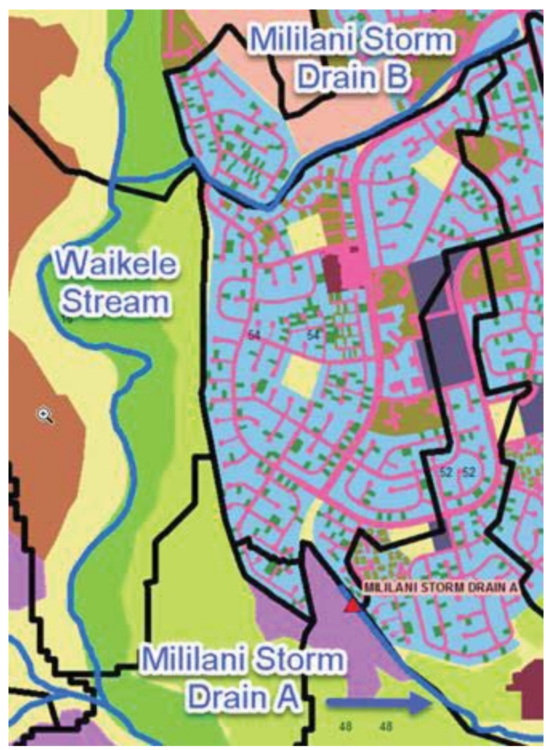

Figure 13: Mililani Storm Drain A Tributary Area (Sub-Basin 54)

There are two key differences between the lowest USGS gage in the study area, Waikele Stream at Waipahu, and the two upper Waikele and Kipapa gages. The first difference is the fact that the lower mainstem of Waikele Stream (below the confluence with Kipapa Stream) does not go dry between storm periods. Some of the baseflow can be attributed to the return flow from higher in the watershed via the deep groundwater. The magnitude of the return flow was set as a function of basin elevation, soil, and cover type to equal approximately 15 percent of the total infiltrated flow based on comparison of simulated and observed flows at the gage location. The second difference is that the intervening drainage area between the upper gages and the lower gage includes a considerable amount of agricultural land. Most of the agriculture in the study area is located below the Wheeler and Kipapa Stream flow gages and above the Waikele Stream at Waipahu flow gage. During an initial calibration of sediment load discussed in further detail in the following section, comparisons of simulated and observed sediment loads indicated that the hydrology calibration was not producing adequate surface runoff to generate surface erosion from bare earth or agricultural areas. Similar to the approach taken for the Kipapa subbasin calibration, it was hypothesized that agricultural areas include both high and low runoff surfaces. This was incorporated into the model by adding a sixth agricultural cover group called 'Ag. High Runoff' that includes 30 percent of the total agricultural area. The 'Ag. High Runoff' cover group is distinguished from the other agriculture cover groups by having a relatively low INFILT rate. The runoff response from the 'Ag. High Runoff' cover group is about 20% higher than the 'Bare Land' cover group, this reflects agricultural roads having soils with more compaction and channelization relative to land cleared for new or redevelopment represented by the 'Bare Land' class.

4.2.2 Monthly and Annual Average Flows

Figure 14a, b, c, and d show comparisons of monthly mean flows simulated by the calibrated model and measured by the USGS at the Kipapa at Wahiawa, Waikele at Wheeler, Mililani Storm Drain A, and Waikele at Waipahu gage sites, respectively. In each Figure 14 plot a linear trendline is fit to each of the three sites and an R-squared value is shown as a measure of fit with the trendline indicating high or low bias; a trendline slope of 1.0 and an R-squared value of 1.0 would indicate there was a simulated and observed match with no variability.

- The plot for Kipapa gage (Figure 14a) presents pre-2004 and post-2007 data separately. The flow gage did not operate for the three year gap between these periods. The monitoring installation should be comparable during both periods, but the simulated flows fit the observed data slightly differently. The most scatter and the lowest R-squared value of the three sites, 0.65, was fit with the pre-2004 data at this site; the post-2007 data fit with an R-squared value of 0.80. The slope of the trendline at the site is very close to 1.0 in both the pre-2004 and post-2007 datasets. The scatter can be partly attributed to a lack of sufficiently representative observed rainfall data to drive the model during some periods.
- The plot for Wheeler (Figure 14b) has much less observed data so the comparison is less meaningful; however, the available data indicate a very good agreement between simulated and observed monthly flow volumes. December 2008, which included the event of record for many sites in central Oahu, shows good agreement between simulated and observed monthly flow volumes. If December 2008 was not included in the fit the R-squared would drop to 0.9025.
- The plot for Mililani Storm Drain A (Figure 14c) has relatively few storms, but the slope of the line is closer to 1.0 than any of the other three USGS gage sites.
- The plot for Waikele Stream at Waipahu (Figure 14d) shows high correlation but a tendency to overestimate discharges in the wettest months of the record.

As one would expect, the same trends shown in comparisons of simulated and observed monthly flow volumes are also apparent comparisons of annual flow volumes in Table 21 – Table 24. The difference between model and the gage volumes at the Kipapa gage (Table 21) varies by year with some very successful matches and some not so successful. Still, on balance, the model does a reasonable job of representing the flow volume in the Kipapa subbasin over the complete simulation period. The difference between the model and the gage volumes at the Waikele Stream at Waipahu gage (Table 24) vary by year— with a better match in more recent years. This is likely partly due to the availability of the

Oahu Forest rain gage after 2006. Prior to 2006 rainfall data for the Koolau region was filled from outside the basin (i.e. Poamoho No. 1 and 2). There is a slight bias to over predict volumes at Waipahu (9%), which is mostly due to a slight over prediction of winter storm volumes. At the Wheeler site the percent error values for the three monitored years look large (123%), but the absolute error is very small due to the fact the this stream is dry for significant periods throughout the year.

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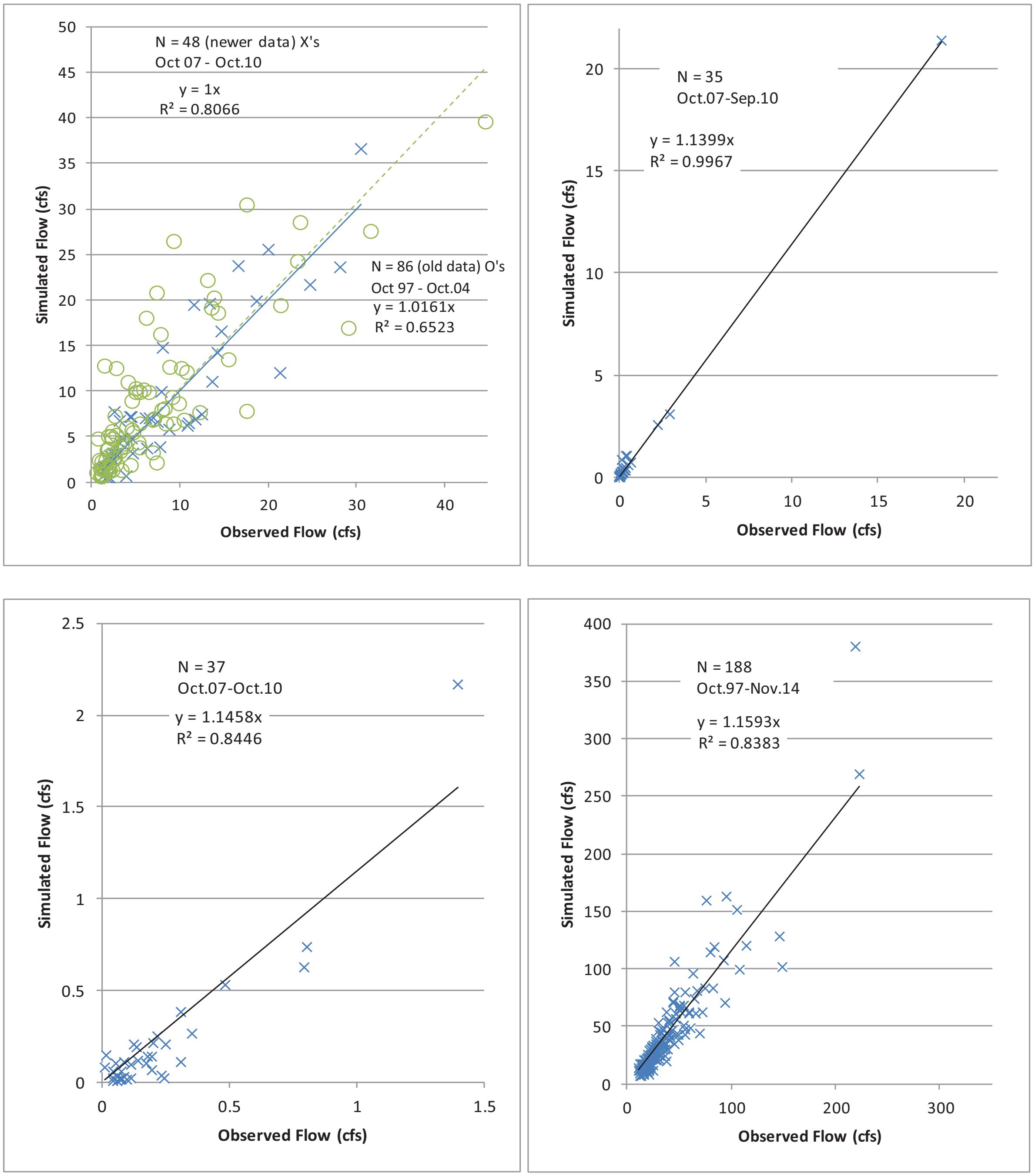

Figure 14a, b, c, and d: Simulated vs. Observed Monthly Mean Flows, Kipapa Stream at Wahiawa (upper left), Waikele Stream at Wheeler (upper right), Mililani Storm Drain A (lower left), and Waikele Stream at Waipahu (lower right)

Table 21: Annual Average Stream Flow, Kipapa Stream at Wahiawa (RCHRES 84)

Water Year	Average Flow (cfs)		Percent Difference
	Observed (USGS)	Simulated	
1998	3.8	2.9	-25%
1999	9.8	5.5	-44%
2000	8.4	6.9	-17%
2001	5.7	6.3	9%
2002	11.2	10.7	-5%
2003	3.8	4.8	25%
2004	15.5	11.7	-25%
2005	N/A	11.3	N/A
2006	N/A	19.7	N/A
2007	N/A	6.8	N/A
2008	7.6	6.6	-14%
2009	8.2	9.8	20%
2010	7.0	7.1	1%
2011	11.0	9.8	-11%
Avg. 1998 – 2004, 2008-2011	8.4	7.4	-12%

Table 22: Annual Average Stream Flow, Waikele at Wheeler (RCHRES 28)

Water Year	Average Flow (cfs)		Percent Difference
	OBSERVED (USGS)	SIMULATED	
1998	N/A	0.09	N/A
1999	N/A	0.50	N/A
2000	N/A	1.35	N/A
2001	N/A	0.21	N/A
2002	N/A	1.15	N/A
2003	N/A	0.49	N/A
2004	N/A	2.75	N/A
2005	N/A	1.18	N/A
2006	N/A	1.26	N/A
2007	N/A	0.56	N/A
2008	0.56	0.67	20%
2009	1.71	2.00	17%
2010	0.15	0.29	96%
2011	N/A	1.34	N/A
Avg. 2008 - 2010	0.81	0.99	23%

Table 23: Annual Average Stream Flow, Mililani Storm Drain A (RCHRES 54)

Water Year	Average Flow (cfs)		Percent Difference
	OBSERVED (USGS)	SIMULATED	
1998	N/A	0.11	N/A
1999	N/A	0.11	N/A
2000	N/A	0.26	N/A
2001	N/A	0.05	N/A
2002	N/A	0.23	N/A
2003	N/A	0.21	N/A
2004	N/A	0.63	N/A
2005	N/A	0.53	N/A
2006	N/A	0.45	N/A
2007	N/A	0.17	N/A
2008	0.24	0.20	-16%
2009	0.29	0.32	10%
2010	0.14	0.08	-40%
2011	N/A	0.53	N/A
Avg. 2008 - 2010	0.22	0.20	-10%

Table 24: Annual Average Stream Flow, Waikeke Stream at Waipahu (RCHRES 10)

Water Year	Average Flow (cfs)		Percent Difference
	OBSERVED (USGS)	SIMULATED	
1998	24.95	17.59	-29%
1999	31.75	30.31	-5%
2000	30.68	37.72	23%
2001	24.20	18.88	-22%
2002	37.52	41.82	11%
2003	18.78	20.65	10%
2004	53.77	61.91	15%
2005	43.37	53.86	24%
2006	61.63	76.31	24%
2007	26.43	28.50	8%
2008	33.89	32.58	-4%
2009	39.84	48.43	22%
2010	24.55	24.06	-2%
2011	46.37	48.34	4%
Avg. 1998 - 2011	35.55	38.64	9%

4.2.3 Single Event Calibration Results

Different approaches were used for calibration of single events for the USGS and the USACE gaging locations based on the form of the observed data available at each location. At the USGS gages, continuous hourly and daily stream flow records were available for use, but at the USACE gages, only weekly interval and periodic instantaneous discharge measurement data were available for the monitoring period. These two calibration targets are discussed separately.

Single Event Hydrograph Comparisons at USGS Gages

Comparisons of simulated and observed hourly time-step hydrographs at the Kipapa at Wahiawa, Millilani Storm Drain, Waikele at Wheeler, and Waipahu gage sites for storm events between December 2003 and December 2008 are provided in Appendix B and are summarized in Table 25. With the exception of the storms/locations marked "No" in the NEXRAD Data column, all of these storms were simulated using NEXRAD radar data. NEXRAD data were unavailable for the 2003 storm and were not used for the Mililani rainfall zone (see discussion in Section 2). As indicated by these figures, the calibrated model does a reasonably good job of tracking the storm hydrographs for these events at the Kipapa at Wahiawa and Waikele Stream at Waipahu sites. Tracking at the Waikele Stream at Wheeler site is decent, with the exception of mismatches during the peaks of the largest storms. The largest event on record, December 12, 2008, is repeated from Appendix B in Figure 15 - Figure 18 for discussion. In Figure 16 and Figure 18, simulated at the Waikele Stream at Wheeler, the Waikele Stream at Waipahu gage both show a slight advance in the timing relative to the observed peak. This trend is exaggerated in this storm event relative to others at these sites. It is not clear if this is an offset in NEXRAD precipitation data time-step, recorded gage record, or a model parameter that is exaggerated during very large storm events.

Table 25: Summary of Single Storm Stream Flow Calibration Events

Figure Number	HSPF RCHRES	Location	Storm Event	NEXRAD Data (Yes/No)	Comment
B1	84	Kipapa at Wahiawa	Dec. 7, 2003	No	
B2	84	Kipapa at Wahiawa	Nov. 4, 2007	Yes	
B3	84	Kipapa at Wahiawa	Feb. 7, 2008	Yes	
18 / B4	84	Kipapa at Wahiawa	Dec. 11, 2008	Yes	
B5	28	Waikele at Wheeler	Nov. 4, 2007	Yes	
B6	28	Waikele at Wheeler	Dec. 5, 2007	Yes	
B7	28	Waikele at Wheeler	Feb. 7, 2008	Yes	
19 / B8	28	Waikele at Wheeler	Dec. 11, 2008	Yes	
B9	54	Mililani Storm Drain A	Nov. 4, 2007	No	
B10	54	Mililani Storm Drain A	Dec. 5, 2007	No	
20 / B11	54	Mililani Storm Drain A	Dec. 11, 2008	No	
B12	10	Waikele at Waipahu	Nov. 4, 2007	Yes	
B13	10	Waikele at Waipahu	Feb. 7, 2008	Yes	
21 / B14	10	Waikele at Waipahu	Dec. 11, 2008	Yes	

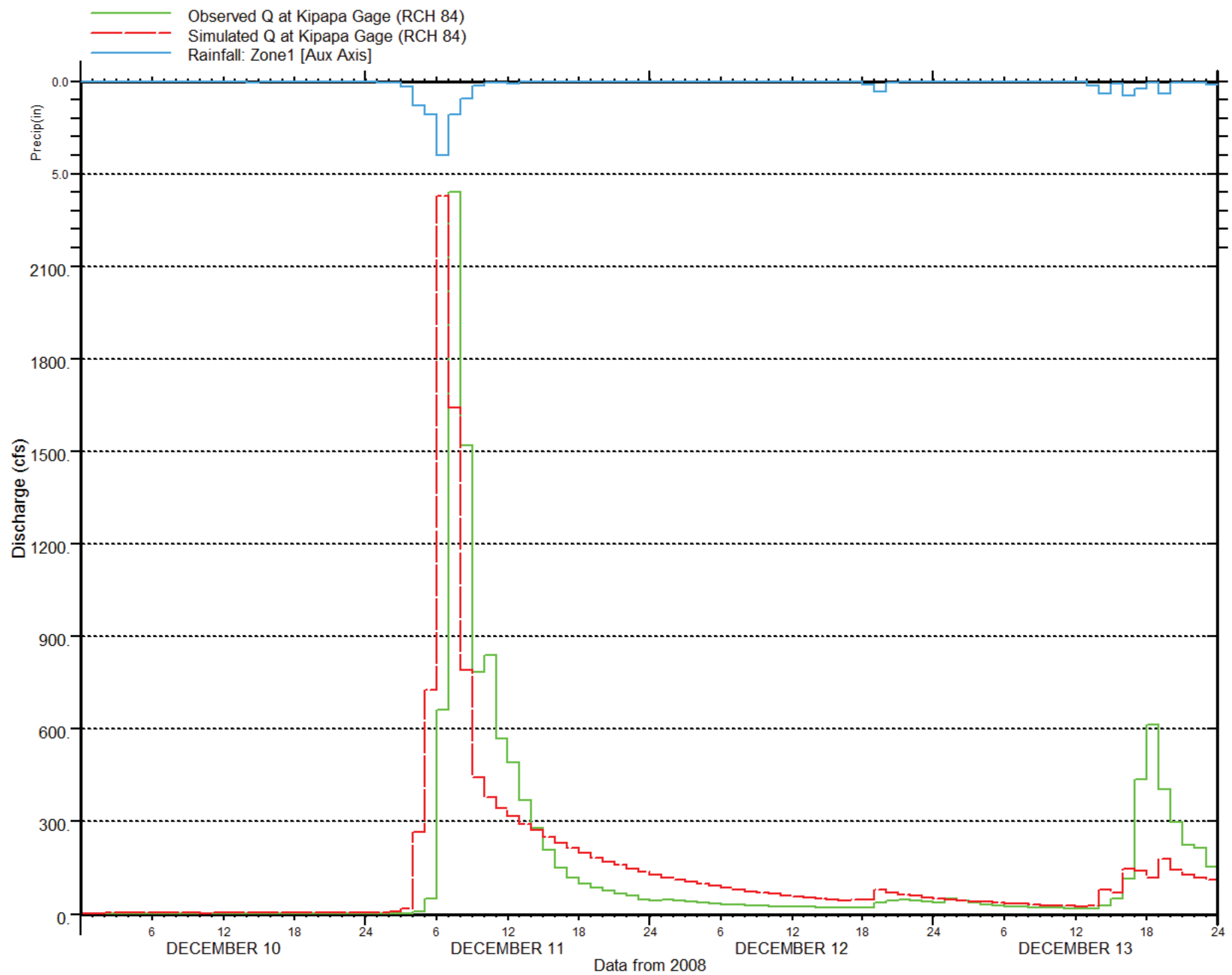

Figure 15: Hourly Stream Flow, Kipapa Stream near Wahiawa, December 11, 2008

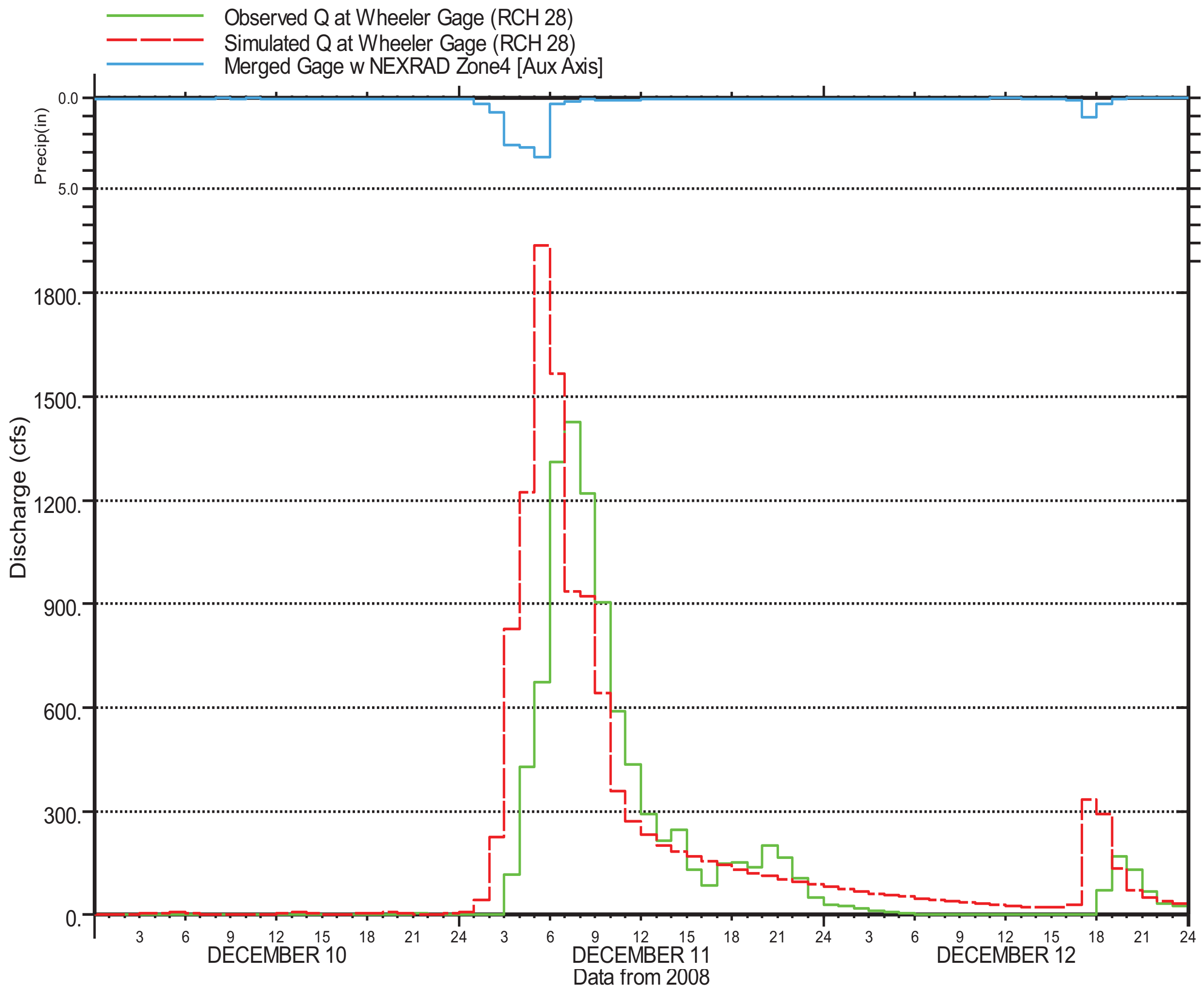

Figure 16: Hourly Stream Flow, Waikele Stream at Wheeler, December 11, 2008

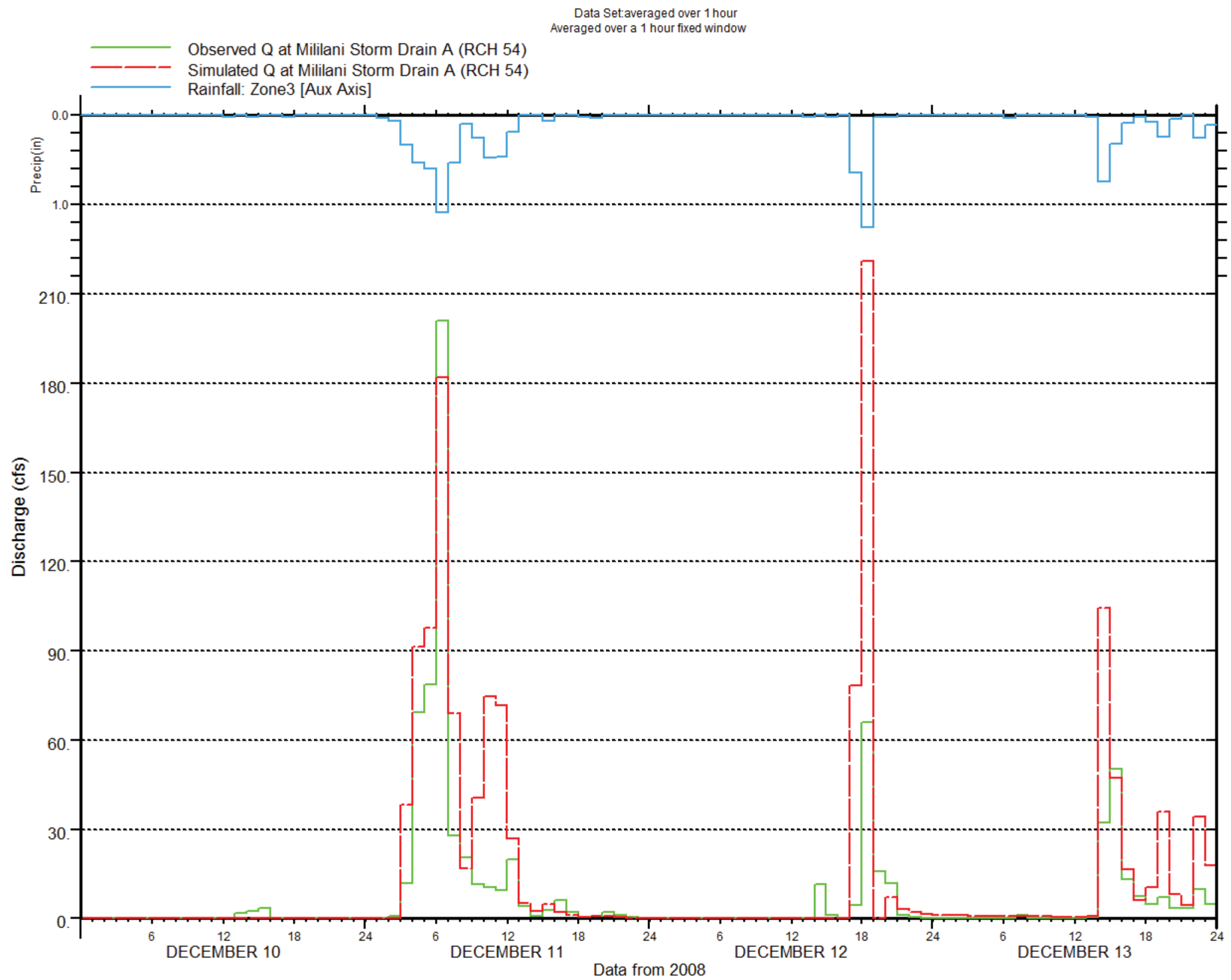

Figure 17: Hourly Stream Flow, Mililani Storm Drain A, December 11, 2008

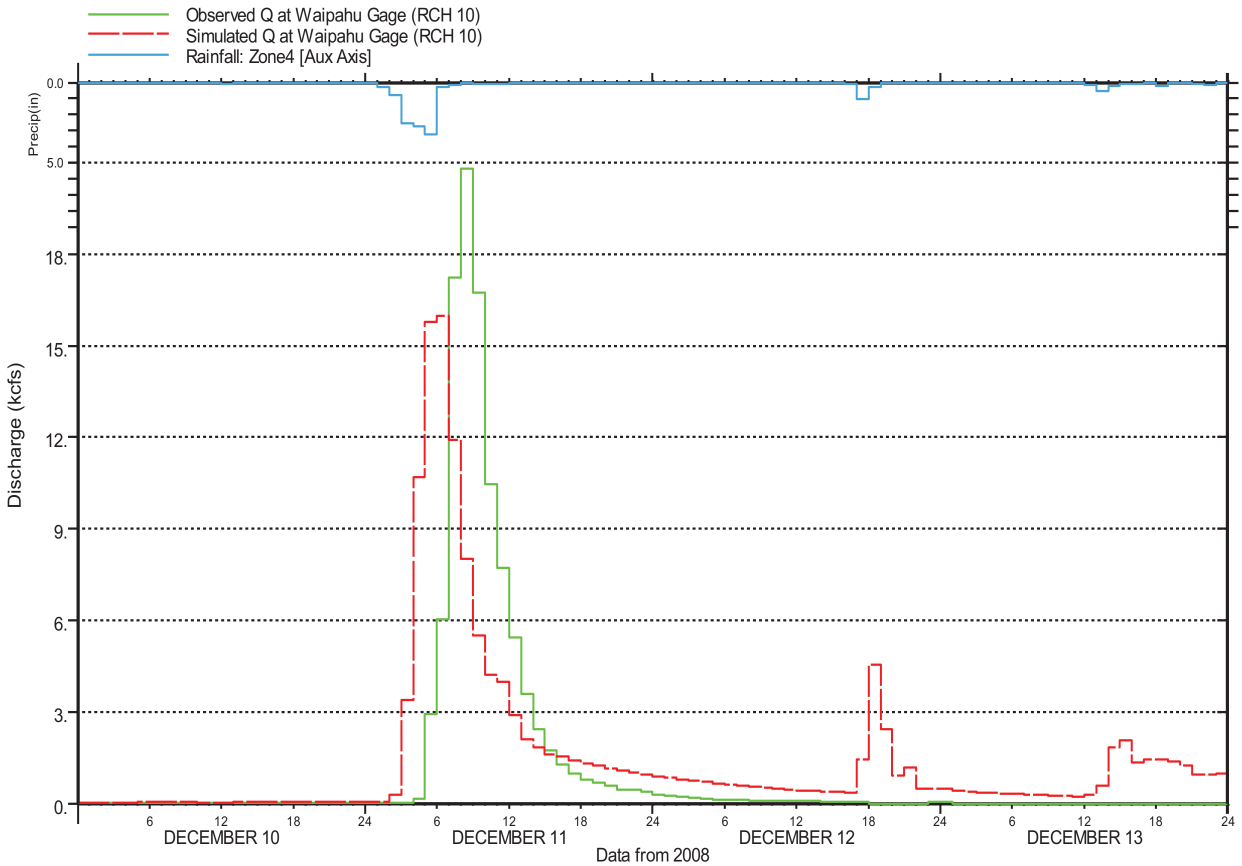

Figure 18: Hourly Stream Flow, Waikele Stream at Waipahu, December 11, 2008 Event

Single Event Volume Comparisons at USACE Gages

Unlike the USGS gaging locations—which NHC was able to visit and discuss with the USGS field staff about the gaging records quality—there is relatively little background information about the USACE monitoring program. Future discussions with the USACE about these records and the conditions in the basin may allow for more improvements or explanations of the calibration to these gaging locations. Table 26 provides a summary of observed and simulated stream flows at USACE gages SW-5, SW-6, SW-11, and SW-12. Summary statistics are provided at the bottom of the table. Time-series of observed flows for these gages are not currently available, so hydrographs could not be provided in the same manner they were for the USGS gage data.

The quality of the calibration to the flow records for the two upland gages SW-5 and SW-6 was poor. These two gages are located above most urban development and below the Waianae Mountain conservation and some military training areas. As stated previously, the stream channel at these gage sites is typically dry, but very high flows can occur during very large storms. This high intensity runoff response was used to confirm that the Waianae mountain soil type must include a very low infiltration rate. However, little could be done to match the flow volumes measured at these sites. At SW-6, which has a much more extensive record than SW-5, the model significantly underpredicted the only two storms recorded (17.6 vs. 48.5 acre-feet on December 11, 2008 and 9.1 vs. 166 acre-feet on January 10, 2011). The data for these gages was not directly used by USACE (2015) for their calibration of a GGSHA distributed hydrology model[6]. That report cites channel infiltration and highly variable precipitation patterns as potential problems with replicating the observed flow records. If the HSPF model parameters for these upland basins were adjusted to match the observed flows, the simulated flows at the USGS Waikele Stream at Wheeler gage would be exceeded. Since the available QA/QC data for the USGS gage is more substantial, it was determined that these data would be used to inform the model calibration of low infiltration soils in the upland areas, but the under prediction of flow volume would be accepted.

Two gages are located immediately downstream of most urban uses in the Upper Waikele Basin. These are the UASCE SW-11 gage, and the USGS Waikele Stream at Wheeler gage. The SW-11 gage is located at the Waikele Stream Kunia Road crossing, and the USGS gage is located about 2,500 feet downstream. The reported flow volumes for the SW-11 gage are much higher than those reported for the USGS gage. For example, the December 11, 2008 event had a reported volume at SW-11 of 1,754 acre-feet, but only 1,055 acre-feet of flow volume was reported by the USGS at the Wheeler gage (both are provided in Table 26; SW-11 data is in italics). The HSPF model simulated a flow volume of 1107 acre-feet at the USGS gage location, which is very close the volume reported by the USGS. A loss of 700 acre-feet between these gages cannot be explained by channel infiltration alone. For the purposes of calibrating this reach of the model, the SW-11 data was largely ignored based on these observations.

At the confluence of Upper Waikele Stream with Waikakalaua Stream is the SW-12 gage. This was the primary data source from the USACE (2015) report that was used for calibration of the HSPF model. Simulated flow volume errors at this gage are typically relatively small (typically less than 20-50 percent error), but some events have errors that are very large, both in percentage and volume. The December 11, 2008 event, for example, had a simulated flow volume of 1,614 acre-feet, but the USACE recorded 3,301 acre-feet. This error in the December 2008 event could not be overcome without deviating from the calibration at the USGS Waikele Stream at Wheeler gage.

[6] The USACE (2015) calibration report states that the GGSHA model was calibrated using data from the USGS gage, SW-11, and SW-12 for seven events between November 13, 2008 and January 2, 2009.

Table 26: Simulated and Observed Event Volumes at USACE Gages (2008 – 2011)

Event Dates	Stream Flow Volumes (acre-ft)								
	Obs. SW-6	Sim. RCH35	Obs. SW-5	Sim. RCH34	Obs. SW-11[1]	Obs. USGS at Wheeler	Sim. RCH28	Obs. SW-12	Sim. RCH24
2/15 - 2/17/08	0.0	0.0	0.0	0.0	*7.5*	2.5	2.2	0.0	2.2
2/24 - 2/25	0.0	0.0	0.0	0.0	*0.0*	1.4	4.6	0.0	5.5
4/12 - 4/12	0.0	0.0	0.0	0.0	*0.0*	0.1	0.5	0.0	0.0
4/16 - 4/16	0.0	0.0	0.0	0.0	*0.0*	0.4	0.0	0.0	0.0
4/25 - 4/25	0.0	0.0	0.0	0.0	*10.4*	0.0	0.0	0.3	0.0
4/26 - 4/26	0.0	0.1	0.0	5.1	*0.0*	4.8	46.4	3.9	72.6
5/21 - 5/23	0.0	0.0	0.0	0.6	*55.8*	10.8	11.4	12.7	18.3
7/15 - 7/15	0.0	0.0	0.0	1.9	*59.3*	19.8	25.7	6.6	43.0
7/23 - 7/28	0.0	0.0	0.0	0.0	*11.6*	0.7	0.2	0.0	0.0
8/12 - 8/12	0.0	0.0	0.0	0.0	*3.2*	0.7	1.9	0.0	1.5
10/13 - 10/15	0.0	0.0	0.0	0.0	*25.0*	5.5	8.1	0.0	9.7
10/25 - 10/26	0.0	0.0	0.0	0.0	*10.9*	2.2	4.8	0.0	4.9
11/13 - 11/16	0.0	0.0	0.0	0.6	*42.4*	12.8	12.4	7.2	16.6
11/22 - 11/22	0.0	0.0	0.0	1.8	*43.3*	13.5	20.2	8.6	32.0
11/29 - 11/29	0.0	0.0	0.0	0.0	*0.0*	0.4	0.4	0.0	0.0
12/2 - 12/2	0.0	0.0	0.0	0.1	*17.9*	10.0	10.6	0.0	13.7
12/10 - 12/16	48.7	5.4	65	146.4	*1754*	1055	1147.4	3301	1739.0
12/26 - 12/28	0.0	0.1	0.0	5.6	*110.9*	29.3	50.7	48.5	76.9
12/28 - 1/2	0.0	0.2	0.0	15.4	*192.5*	56.7	130.7	113.4	206.2
1/7 - 1/7/09	0.0	0.0	0.0	0.0	*0.0*	0.9	0.0	0.0	0.0
1/10 - 1/11	0.0	0.0	0.0	0.1	*11.0*	4.6	7.5	8.1	11.6
1/15 - 1/17	0.0	0.0	0.0	3.2	*40.6*	19.4	28.3	39.2	44.0
10/22 - 10/22	0.0	0.0	-	0.0	*0.0*	0.0	0.0	0.1	0.0
10/23 - 10/23	0.0	0.0	-	0.0	*0.0*	0.0	0.0	0.0	0.0
11/3 - 11/3	0.0	0.0	-	0.0	*0.0*	0.1	2.8	0.0	1.8
11/14 - 11/14	0.1	0.0	-	0.0	*0.0*	0.4	0.0	0.0	0.0
11/26 - 11/26	0.0	0.0	-	0.9	*0.7*	7.7	14.1	0.2	22.9
12/3 - 12/3	0.0	0.0	-	1.3	*0.0*	4.7	12.8	0.0	20.9
12/31 - 12/31	0.0	0.0	-	0.0	*2.4*	0.5	0.5	0.0	0.0
2/2 - 2/2	0.3		-		*0.0*	-		0.0	
1/29 - 1/29/10	0.0	0.0	-	1.2	*0.0*	9.3	15.3	0.4	25.8
2/2 - 2/2	0.0	0.0	-	1.2	*0.0*	9.9	14.4	0.1	21.0
2/26 - 2/26	0.0	0.0	-	0.0	*6.2*	0.0	0.0	0.0	0.0
4/1 - 4/1	0.0	0.0	-	0.0	*2.4*	0.0	0.0	0.0	0.0
4/4 - 4/7	0.2	0.0	-	2.2	*11.2*	20.8	27.9	23.7	36.8
5/2 - 5/3	0.0	0.0	-	0.0	*2.9*	6.1	5.9	1.0	7.0
5/28 - 5/28	0.0	0.0	-	0.0	*0.0*	3.6	4.6	-	5.5

Event Dates	Stream Flow Volumes (acre-ft)								
	Obs. SW-6	Sim. RCH35	Obs. SW-5	Sim. RCH34	Obs. SW-11[1]	Obs. USGS at Wheeler	Sim. RCH28	Obs. SW-12	Sim. RCH24
7/3 - 7/3	-	0.0	-	0.0	-	0.1	1.2	-	0.1
9/22 - 9/22	-	0.0	-	0.0	-	0.5	4.3	-	5.1
9/29 - 10/1	-	0.0	-	0.3	-	10.7	10.3	-	15.8
12/26 - 12/28	0.0	0.0	-	7.9	*6.0*	-	67.7	52.1	107.1
1/10 - 1/17/11	166.1	1.0	-	57.1	*180.0*	-	569.0	597.4	887.8
2/6 - 2/22	13.6	0.0	-	1.8	*28.8*	-	30.2	9.9	45.7
3/4 - 3/5	6.7	0.1	-	7.0	*26.0*	-	62.7	25.6	94.6
4/6 - 4/8	0.4	0.0	-	0.0	*36.4*	-	0.0	21.7	0.0
5/4 - 5/9	3.5	0.0	-	0.0	*85.1*	-	0.0	37.1	0.0
6/3 - 6/4	0.0	0.0	-	1.7	*24.9*	-	23.0	10.4	36.8
Summary Statistics									
Mean Error		-5.4		5.3			7.7		-17.2
Mean Absolute Error		5.4		5.3			7.9		60.0
Maximum Absolute Error		165.0		81.7			91.9		1562.9

[1] Observed flow volumes at SW-11 were not used for calibration and are provided for reference only. Volumes reported at this gage are generally higher than the USGS gage which is located only a short distance downstream from SW-11. Further dialog with USACE is required before using this record.

4.3 Sediment

Similar to stream flow, the model parameters controlling simulation of sediment production, delivery and transport were also calibrated by setting an initial set of parameters and modifying those to improve the match between simulated and observed data. Daily average total suspended sediment (TSS) concentrations at the same three USGS gages that were also used in the hydrology calibration (Waikele at Wheeler and Waipahu and Kipapa at Wahiawa) were used for the comparison. The effort focused on 2007 to 2010, the period for which suspended sediment data were collected by the USGS for the City and County of Honolulu.

It cannot be over stressed how connected the hydrology and sediment delivery processes are and that the sediment calibration quality is dependent on the quality of the hydrology calibration. HSPF generates sediment from the land surface and from in-channel processes. Land surface derived sediment is produced from the land segments (PERLNDs and IMPLNDs) as washoff and optionally gully (scour) erosion (see Figure 19); both require surface flow (SURO) to be produced for any sediment to be transported to the stream. In-channel flow erosion is also dependent on hydrology but it is instead related to the erosive potential of that flow in the channel which is directly related to stream flow velocity. The relative contribution of land surface or in-channel processes to the concentration of suspended sediment observed is also an important part of sediment calibration. No comprehensive data quantifying the relative contribution of land surface or in-channel processes was available at the time of this report, but a current USGS study of sediment sources is on-going and should provide valuable information to the question. Instead, this effort focused on sharing the sediment load between both land surface and in-channel sources, but the proportions could be modified when additional data becomes available.

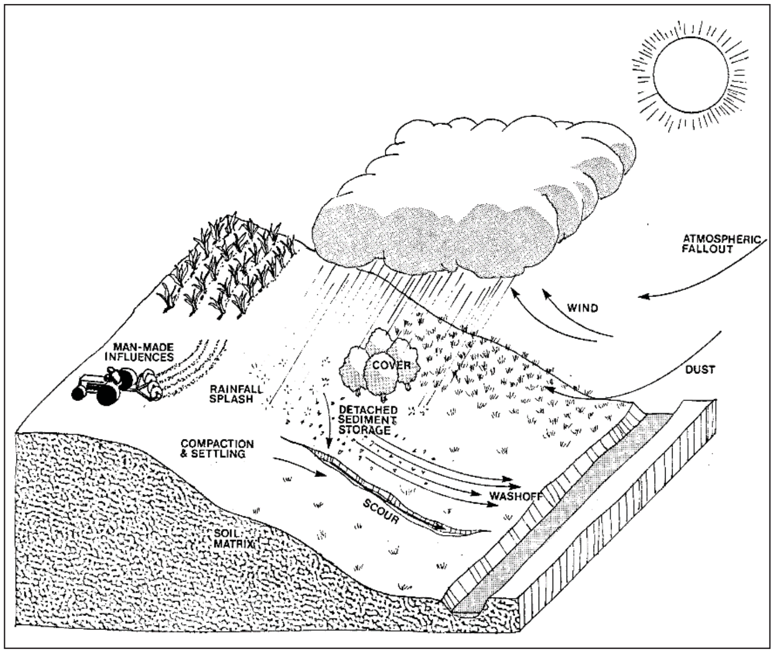

Figure 19: Schematic showing land segment derived sediment processes (EPA, 2005)

A tabulation of model parameters for surface erosion processes is presented in Table 27. The surface washoff processes are calibrated using parameters that control both the detachment and accumulation of sediment (SMPF, KRER, JRER, AFFIX, COVER, and NVSI) and those controlling the capacity to washoff or deliver the accumulated sediment to the receiving stream (KSER and exponent JSER). The Supporting Management Practices Factor (SMPF) is used to simulate a reduction in erosion achieved by use of erosion control practices; a factor of 1.0 represents no reduction, and a factor of 0.3 would correspond to contour strip cropping or similar practice. Detail regarding control practices from agricultural and other land uses within the Waikele Stream watershed was not available at the time of this study, so no reduction in the SMPF factor was assumed. The detachment coefficient (KRER) is dependent on soil type; it was set equal to the USLE K values from the SSURGO soils dataset and not varied during calibration. The values of AFFIX and NVSI were determined by simulating the detached sediment accumulated on the surface (DETS) and adjusting AFFIX and NVSI so that the net accumulation over a long period is equal to zero.

Sediment load from gully erosion simulated directly as a power function of surface runoff independent of sediment accumulation calculations mentioned above. The scour or gully parameters —KGER and exponent JGER—are not always used in mainland U.S. applications, but the mountainous areas of the watershed have steep gullies with exposed soil susceptible to scour. The potential scour of gullies is increased in the mountainous areas of Waikele Stream where feral pigs are actively creating trails and rototilling. In addition, as noted in the geomorphic assessment (NHC, 2016), landslides in steep mountainous areas of the watershed represent a significant source of fine sediment to stream channels. This is especially the case on the wetter east side of the watershed in the head waters of Kipapa Stream and Waikakalaua Stream where higher intensities and volumes of rainfall increase soil saturation. The gully erosion parameters were used to represent these sediment sources.

Table 27: Land Segment Sediment Calibration Parameters

Land Cover	PERLND IDs	Sediment Accumulation					Washoff		Gully Scour	
		SMPF	KRER	JRER	AFFIX	NVSI	KSER	JSER	KGER	JGER
Forest	101-216	1	0.10-0.40	2	0.013	3-4	10	2	1.5	1.3
Grass Urban	201-346	1	0.20-0.46	2	0.007	10	10	2	None	None
Scrub-Shrub	401-496	1	0.15-0.40	2	0.013	4	10	2	1.5	1.3
Pasture	521-546	1	0.15-0.40	2	0.007	10	10	2	None	None
Golf Course	581-586	1	0.30-0.50	2	0.007	10	10	2	None	None
Bare Land	601-606	1	0.50	2	0.007	10	10	2	0.15	2.5
Ag. High Runoff	671-696	1	0.15-0.30	2	0.007	10	10	2	1.75	3.0
Fallow	721-726	1	0.30-0.50	2	0.007	10	10	2	None	None
Seed Corn	771-796	1	0.40-0.60	2	0.007	10	10	2	1.75	3.0
Truck Crop	821-846	1	0.40-0.60	2	0.007	10	10	2	1.75	3.0
Pineapple	871-896	1	0.30-0.50	2	0.007	10	10	2	1.05	2.0
Wetland and Water	901-906	1	0.05-0.20	2	0.016	4	10	2	None	None

SMPF: Management Practice (P) factor from USLE; KRER: Coefficient in the soil detachment equation; JRER: Exponent in the soil detachment equation: AFFIX: Daily reduction in detached sediment; NVSI: Atmospheric additions to sediment storage; KSER: Coefficient in the sediment washoff equation; JSER: Exponent in the sediment washoff equation; KGER: Coefficient in the soil matrix scour equation; JGER: Exponent in soil matrix scour equation.

Sediment Calibration Objectives

Several related criteria were used to guide sediment calibration. In approximate priority order these include:

1. Match daily observed suspended sediment loads on days when simulated hydrographs are reasonably close to observed hydrographs at the three gaging sites noted in the USGS (2015) report—especially for the record flood and extreme sediment load of December 11, 2008.
2. Match total event loads and TSS concentrations reported by UASCE (2016) for Upper Waikele Stream gage sites.
3. Simulate long-term average suspended sediment yields at the USGS Waipahu site and Upper Kipapa stream site that are reasonably consistent with past studies as documented in the geomorphic assessment

4. Provide a reasonable estimate of the in-channel contributions resulting from channel widening during extreme events as observed in December 11, 2008 event and summarized in the geomorphic assessment
5. Simulate average annual suspended sediment contributions from different processes, land uses categories, and subwatersheds that are reasonably consistent with the sediment budget included in the geomorphic assessment.

4.3.1 Sediment Calibration Assumptions

There are 10 sediment parameters affecting each PERLND's sediment yield, as well as several associated with transport, erosion and deposition in channel reaches. In order to reduce the degrees of freedom in sediment calibration to a more manageable level consistent with available data, several parameters were set to be uniform or in a range that would not influence downstream load estimates. These assumptions are listed below:

1. Soil detachment coefficient KRER values fall within the maximum range recommended by Basins Technical Note 8, but vary among land uses and soil types. All JRER values are set at 2.0.
2. The PERLND transport capacity coefficient KJER was assumed to be constant at its maximum recommended value of 10 in order to reduce sensitivity of sediment delivery to surface transport.
3. KGER representing gullying was set to zero, except for selected PERLNDS of low to moderate permeability to simulate gullying as well as infrequent landslides.
4. The RCHRES deposition threshold, TAUCD, for silt and clay is set at its lowest possible value to convey silt and clay as washload; a condition consistent with the observation that minimal fine sediment is found in watershed stream beds.
5. RCHRES scour threshold, TAUCS, values were set to supply sediment during infrequent high flow events to mimic observed channel widening as observed during the December 11, 2008 event and analyzed by the geomorphic assessment.
6. The RCHRES parameters for sand transport, KSAND, are configured to convey sand as washload.

4.3.2 Sediment Calibration Results — Suspended Sediment Loads from Individual Storm Events

Sediment calibration results for individual storm days are summarized in Table 28, below. As shown in the table in almost all cases, simulated mean daily discharge is within approximately 30 percent of observed daily discharge, and simulated daily suspended sediment yields are similarly close to the USGS's observed suspended sediment yield. Of particular importance is the agreement between the model and observed sediment yield for the storm of December 11, 2008, the event of record, at all three gage sites. As has been observed by DFM-SWQ staff, the USGS, and NHC's geomorphic assessment, average annual sediment yields in Waikele Stream watershed are disproportionately influenced by a relatively few, large storm events.

Table 28: Comparison of Simulated and Observed Suspended Sediment for Individual Storm Days

Date	USGS Mean Daily Q (cfs)	HSPF Mean Daily Q (cfs)	% DIFF	USGS Daily Sediment Load (tons)	HSPF Daily Sediment Load (tons)	% DIFF
Waikele Stream at Waipahu						
	cfs	cfs		tons	tons	
11/4/2007	1420	1305	-8%	10500	8604	-18%
2/6/2008	280	252	-10%	1800	857	-52%
12/11/2008	4270	4080	-4%	227000	212420	-6%
Waikele Stream at Wheeler						
11/4/2007	80	72	-9%	481	386	-20%
2/6/2008	6	5	-27%	12	11	-8%
12/11/2008	384	446	16%	6600	7749	17%
Mililani Storm Drain A[1]						
11/4/2007	16	15	-8%	8	7	-11%
2/6/2008	1	< 0.1	NA	< 0.1	< 0.1	0%
12/11/2008	20	30	52%	19	21	9%
Kipapa Stream at Wahiawa						
11/4/2007	306	265	-13%	755	727	-4%
2/6/2008	106	113	7%	417	429	3%
12/11/2008	352	397	13%	2350	2455	4%

[1] The observed flow and daily sediment loads listed for Mililani Storm Drain A reflect an adjustment to the USGS published flow record. See related discussions in Sections 4.1 and 4.3.4.

Comparisons of simulated and observed daily sediment load pollutographs at the Kipapa at Wahiawa, Waikele at Wheeler, and Waikele at Waipahu gage sites for storm events between November 2007 and December 2008 are provided in Figures C1-C10 in Appendix C and summarized in Table 29. These figures provide daily mean sediment load as tons per day for the same storm events presented for the hydrology calibration. Daily mean flow hydrographs are shown with the pollutographs to aid in interpretation. The figures show good agreement between simulated and observed daily sediment loads at all four gage sites during most storm periods shown; notable exceptions being the December 5, 2007 event at the Waikele at Wheeler site. The cause for mismatches between simulated and observed sediment loads can be partly attributed to poor rainfall data, mass-wasting, or other processes not explicitly included in the model. Another challenge with the Upper Waikele Stream region (i.e. upstream of the Waikakalaua confluence) is a relatively rapid change from pineapple agriculture to fallow and/or other land uses between the period 2005 and 2008. As part of the calibration process Google Earth imagery from late 2008 was reviewed and some pineapple areas were shifted to fallow as part of the calibration.

Table 29: Summary of Sediment Calibration Months

Figure Number	HSPF RCHRES	Location	Period (Month)	NEXRAD Data (Yes/No)	Monthly Load (tons)	
					Observed	Simulated
C1	84	Kipapa at Wahiawa	Nov. 4, 2007	Yes	778	790
C2	84	Kipapa at Wahiawa	Feb. 7, 2008	Yes	419	464
C3	84	Kipapa at Wahiawa	Dec. 11, 2008	Yes	2,686	2,557
C4	28	Waikele at Wheeler	Nov. 4, 2007	Yes	486	410
C5	28	Waikele at Wheeler	Dec. 5, 2007	Yes	89	303
C6	28	Waikele at Wheeler	Feb. 7, 2008	Yes	20.3	62.1
C7	28	Waikele at Wheeler	Dec. 11, 2008	Yes	6,956	8,164
C8	54	Mililani Storm Drain A	Nov. 4, 2007	No	10.3	8.2
C9	54	Mililani Storm Drain A	Dec. 5, 2007	No	10.0	8.2
C10	54	Mililani Storm Drain A	Feb. 7, 2008	No	4.2	2.9
C11	54	Mililani Storm Drain A	Dec. 11, 2008	No	26.3	33.8
C12	10	Waikele at Waipahu	Nov. 4, 2007	Yes	10,656	8,876
C13	10	Waikele at Waipahu	Feb. 7, 2008	Yes	1870	1,774
C14	10	Waikele at Waipahu	Dec. 11, 2008	Yes	229,090	226,720

4.3.3 Sediment Calibration Results — Upper Waikele at USACE Gages

Total sediment load data provided in the USACE (2015) report was utilized for calibration of the HSPF model sediment parameters in the Waianae Range and developed portions of Upper Waikele stream. Total observed sediment loads were reported in Table 9 by USACE (2015) for seven events at gage sites SW-11 and SW-12. Those observed sediment loads and the simulated HSPF sediment loads are reported for the SW-11 site in Table 30, the USGS gage Waikele Stream at Wheeler site (for comparison) in Table 33, and the SW-12 site in Table 32.

Like the flow data at SW-11, discrepancies also exist for the reported loads for the SW-11 site relative to the USGS Waikele Stream at Wheeler gage sediment data. As a result, the loads reported for SW-11 in Table 30 were only used for informational purposes. A comparable tabulation of loads for the USGS gage has been provided as Table 31 to show how well the model matches the data at that site. The reported loads at SW-11 could not be matched without deviating from the data reported by the USGS.

Downstream from the USGS gage, at SW-12, the match between the simulated and observed loads are split, with three of the events having simulated higher loads than those reported, and three simulating lower loads. The biggest absolute error listed in Table 32 is for the December 11, 2008 event, which was under simulated by over 1000 tons (10 percent). However, this error can be partly explained by considering the change in agricultural land use in this area. On the south side of Waikele Stream there are approximately 190 acres of agricultural land that is tributary to the SW-12 gage. This land was modeled as fallow in the tabulated results, but changing the use to active pineapple reversed the trend and resulted in an over estimate of the observed load at SW-12 by more than 30 percent. The impact of this change highlights both the sensitivity of the calibration to the assigned use for the land (which is rapidly changing from pineapple to other uses), and also of the relatively high loads being assigned to agricultural uses without any monitoring data for exclusively agricultural areas.

Table 30: Simulated and Observed Sediment Loads for Fall 2008 Events at SW-11 (Reach 29)

Event Start-End Date	USACE Rating of Data Quality	HSPF Model Flow Volume Calibration Agreement at USGS Gage (% Error)	Observed Load (tons)	Simulated (tons)
Nov. 13-16, 2008	Excellent	-2%	70	23
Nov. 22, 2008	Good	+50%	7.4	20
Nov. 29, 2008	NA	0%	0.0	0.3
Dec. 2, 2008	Fair	+6%	2.2	5.4
Dec. 10-16, 2008	Poor	+9%	9,844	5,682
Dec. 26-28, 2008	Poor	+73%	70	18
Dec. 28, 2008 – Jan. 2, 2009	Poor	+130%	281	51

Table 31: Simulated and Observed Suspended Sediment Loads for Fall 2008 Events at USGS Waikele Stream at Wheeler (Reach 28)

Event Start-End Date	USACE Rating of Data Quality	HSPF Model Flow Volume Calibration Agreement at USGS Gage (% Error)	Observed Load (tons)	Simulated (tons)
Nov. 13-16, 2008	Good	-2%	12	21
Nov. 22, 2008	Good	+50%	2.1	19
Nov. 29, 2008	Fair	0%	0.0	0.2
Dec. 2, 2008	Fair	+6%	1.0	1.5
Dec. 10-16, 2008	Good	+9%	6,887	7,970
Dec. 26-28, 2008	Fair	+73%	0.5	18
Dec. 28, 2008 – Jan. 2, 2009	Good	+130%	10	61

Table 32: Simulated and Suspended Sediment Loads for Fall 2008 Events at SW-12 (Reach 24)

Event Start-End Date	USACE Rating of Data Quality	HSPF Model Flow Volume Calibration Agreement at SW-12 (% Error)	Observed Load at SW-12 (tons)	Simulated Load at Reach 24 (tons)
Nov. 13-16, 2008	Good	-15%	8.9	22.5
Nov. 22, 2008	Fair	+96%	3.1	22.7
Nov. 29, 2008	Good	0%	0	0.3
Dec. 2, 2008	Good	0%	0	2.9
Dec. 10-16, 2008	Fair	-51%	10,939	9897.4
Dec. 26-28, 2008	Poor	+24%	24	20.4
Dec. 28, 2008 – Jan. 2, 2009	Poor	+41%	135	65.6

4.3.4 Sediment Calibration Results- 2008-2010 Average Annual Suspended Sediment at USGS Gages

The USGS (2015) collected contemporaneous discharge and suspended sediment data in the Waikele watershed during water years 2008-2010. They reported sediment yields at four gage locations (Kipapa, Wheeler, Mililani, and Waipahu) and their respective subbasins, plus an additional subbasin, referred to as “Waipahu Exclusive”, for which values were determined by subtraction of the three smaller subbasin’s values from the whole watershed, as represented by the Waipahu gage site. Table 33 compares their results with the results of the calibrated HSPF model.

Table 33: Comparison of HSPF Simulated and USGS-reported Suspended Average Sediment Yields for Water Years 2008 – 2010

Basin/Subbasin	Area (sq mi)	USGS Study (tons/yr)	HSPF Model[1] (tons/yr)	USGS (tons/yr/sq mi)	HSPF Model (tons/yr/sq mi)*
Wheeler	6.72	2600	3143	387	447
Kipapa	4.28	1690	2355	395	550
Mililani	0.56	29[2]	30	51[2]	54
Waiphau Exclusive	34.22	78200	80313	2329	2347
Waipahu	46.1	82500	85841	1828	1862

[1]Approximately 16% of the suspended sediment computed by the calibrated HSPF model is associated with channel widening taking place during the December 11, 2008 flood event

[2] This total reflects an adjustment to the USGS flow record for Mililani Storm Drain A.

It should be noted that over 90 percent of both the USGS and HSPF 3-year totals at Waipahu are contributed by water year 2009, and indeed by a single day: December 11, 2008. The corresponding percentages for the other subbasins are 85 percent at Wheeler, 46 percent at Kipapa, but only 22 percent at Mililani, according to the USGS. The HSPF model percentages closely match the USGS percentages, if the modifications to the Mililani record discussed previously in Section 4.1 are utilized. The recalculated load from Mililani for the December 11, 2008 event was 19 tons, while the USGS’s published value is 3.2 tons.

Channel Contributions

The USGS (2015) concluded that channel erosion accounted for an insignificant amount (<1 percent) of Waikele Watershed fine sediment yield over the 2008-2010 study period. However, this was based, in part, on bed material samples indicating a very low percentage of silt and clay. On the other hand, the USGS’s channel cross-section measurements indicated that up to 12 feet of channel widening occurred in pool-riffle reaches along the mainstem of Waikele stream, with lesser amounts occurring in Waikakalaua and Kipapa stream reaches. NHC’s geomorphic assessment (2016) concludes that greater than 25 percent of sloughed bank material would have been transported to Waipahu as fine suspended sediment. Based on measured width changes, bank height estimates, stream lengths, and bulk density, this would account for between 25,000 and 30,000 tons or as much as 17 percent of the sampled load at Waipahu. HSPF channel reach parameters controlling scour were set to yield approximately this much sediment with the bulk of scour assigned to the mainstem reaches downstream of Wheeler, and smaller percentages associated with Waikakalaua, Kipapa, and other tributaries.

The allocation of a moderate percentage of suspended sediment yield to observed channel widening has the effect of moderately reducing the estimated proportion of the total basin load contributed by the "Waipahu Exclusive" subbasin and, by extension, the hillslope erosion contributed by agricultural land which predominates in this area. Regardless of this reduction, the HSPF model still ascribes a very high percentage of the total load and the load per square mile to this subbasin, substantially in agreement with USGS conclusions.

4.3.5 Long Term Average Sediment Budget and Comparison with Geomorphic Assessment Sediment Budget

The HSPF model was run using the available meteorological record from water year 1990 through water year 2012 and compared with the sediment budget developed by NHC during the Geomorphic Assessment phase of this project. The sediment budget for fine sediment yield (silt and clay only) was developed based on field reconnaissance, available Waikele Watershed sediment load data including the recent USGS study, reported values of land use related sediment production for other Oahu watersheds, and other literature values. HSPF requires the user to set the percentages of silt, clay, and sand sized sediment delivered from hillslopes to channels based on soil data; however, once sediment reaches the channel, the erosion and routing of these three size classes are individually tracked by the model, and it is possible to output results for only fine sediment. Table 34 and Table 35 compare the HSPF model with the geomorphic assessment at the scale of the entire watershed, as represented by the Waipahu USGS site and five sub-watersheds. Note that in this tabulation, the Kipapa subwatershed refers to the entire Kipapa stream drainage area above the confluence of Kipapa stream with Waikele Stream; Upper Waikele subwatershed refers to the drainage area to Waikele stream above the Waikakalaua confluence; Waianae subwatershed refers to the Huliwai and Poliwai gulch drainage areas; and Lower Waikele subwatershed is the remainder of the drainage area to Waikele Stream not included in the other four subwatersheds. Water year 2009 was omitted from the totals in Table 35 because December 2008 event it is an extreme outlier that skews the annual load averaged over the 15 year simulation.

At the scale of the entire watershed, the average annual fine sediment yield computed by the HSPF model agrees quite closely with the geomorphic assessment. Similarly, while the exact numbers differ somewhat, both budgets rank agriculture as the largest land use contributor by far to total fine sediment yield, followed by natural areas. Additionally, both budgets rank urban land use areas as the lowest contributors. Channel erosion associated primarily with bank sloughing represents approximately 17 percent of the fine sediment budget in the geomorphic assessment and the HSPF derived budget. At the subwatershed scale, both budgets rank Kipapa and Waianae subwatersheds as the largest contributors, followed by Lower Waikele, Waikakalaua, and Upper Waikele. The biggest discrepancy between the two budgets are the loads at Kipapa Stream and Upper Waikele. The load at Upper Waikele is lower than that obtained by the geomorphic assessment partly due to the new data acquired from the Army that was not available to NHC (2016). The observed load at SW-12 is low relative to what the geomorphic assessment would have predicted. The resulting calibration for Upper Waikele Stream has a lower sediment contribution predicted for that basin.

Table 34: Geomorphic Assessment Average Annual Fine Sediment Budget

	Waikakalaua	Kipapa	Upper Waikele	Waianae	Lower Waikele	Watershed
	(tons)	(tons)	(tons)	(tons)	(tons)	(tons)
AG Total	190 (7%)	2830 (34%)	3460 (71%)	6840 (87%)	5220 (83%)	18500 (61%)
CONSERVATION /NATURAL Total	1850 (71%)	3440 (41%)	280 (6%)	230 (3%)	10 (0%)	5830 (19%)
URBAN Total	40 (2%)	140 (2%)	410 (8%)	10 (0%)	50 (1%)	650 (2%)
Hill Slope Subtotal	2080 (80%)	6410 (76%)	4150 (85%)	7080 (90%)	5280 (84%)	24980 (83%)
Channel	560 (22%)	1960 (23%)	750 (15%)	820 (10%)	1010 (16%)	5100 (17%)
Total Yield	2600	8400	4900	7900	6300	30100

Table 35: HSPF Average Annual Fine Sediment Yield based on WY 1997 – 2008 and 2010-2011

	Waikakalaua	Kipapa	Upper Waikele	Waianae	Lower Waikele	Watershed
	(tons)	(tons)	(tons)	(tons)	(tons)	(tons)
AG Total	222 (12%)	6076 (48%)	98 (8%)	5612 (91%)	3468 (58%)	15477 (56%)
CONSERVATION /NATURAL Total	836 (46%)	2450 (19%)	529 (43%)	463 (7%)	1354 (23%)	4279 (15%)
URBAN Total	276 (15%)	777 (6%)	617 (50%)	79 (1%)	264 (4%)	3386 (12%)
Hill Slope Subtotal	1334 (74%)	9303 (74%)	1244 (101%)	6155 (100%)	5086 (85%)	23142 (83%)
Channel	464 (26%)	3309 (26%)	-16 (-1%)	24 (0%)	897 (15%)	4678 (17%)
Total Yield	1798	12613	1229	6179	5983	27800

5 CONCLUSION

The HSPF water discharge and fine sediment, water quality model was developed to conduct planning level analyses of management practices and to assist with future TMDL compliance. The model was comprised of a standard set of runoff response units applied in other basins in Central Oahu and was calibrated to observed flow and sediment data and was also influenced by the geomorphic assessment and sediment budget developed for this project NHC (2016).

The resulting match to annual flow volumes ranged from 90 percent to 123 percent and the match to USGS monitored sediment yields (Table 33) is quite good. Yields range from 54 to 2347 tons/year/square mile, depending on which portion of the basin. Individual storms targeted during calibration matched within 0 and 52% (Table 28). Given the high degree of spatial variability in local rainfall data, changing land use, and dynamic hydrologic processes active in the mountainous regions of this watershed, the calibration was considered adequate for the objectives of the project.

Additional monitoring data would help refine several areas of uncertainty within the model calibration. Gaging of agricultural sub-basins could provide a measure loads from individual agriculture crop types and refine the loadings from those areas. A second area of uncertainty is related to questions surrounding the flow and sediment data collected by USACE (2015). Some of these questions could be resolved with a site visit and/or dialog with staff involved in their monitoring program.

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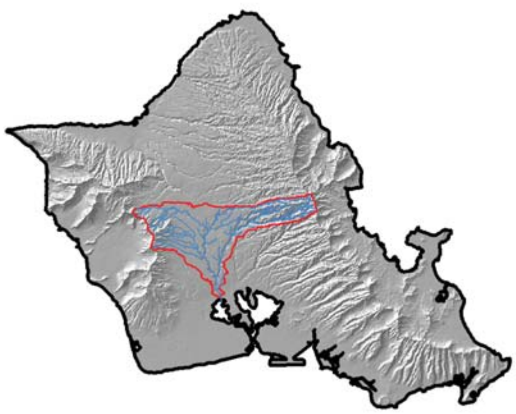
Appendix A: Geomorphic Assessment of Waikele Watershed – Sediment Budget (NHC, 2016)

Central Oahu Watershed Studies Geomorphic Assessment of Waikele Watershed – Sediment Budget

January 27, 2016




northwest hydraulic consultants

water resource specialists

CENTRAL OAHU WATERSHED STUDIES

GEOMORPHIC ASSESSMENT OF WAIKELE WATERSHED - SEDIMENT BUDGET

Submitted to:

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Honolulu, HI 96813

Submitted by:

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Revised on:
November 18, 2011
September 30, 2014
January 27, 2016

NHC Project 21831

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List of Acronyms

AFSY	Annual fine sediment yield
ENV	City and County of Honolulu Department of Environmental Services
DOH	State of Hawaii Department of Health
HSPF	Hydrologic Simulation Program Fortran
NHC	Northwest Hydraulic Consultants
PB	Parsons Brinckerhoff, Hawaii
TMDL	Total Maximum Daily Load
USGS	United States Geological Survey
USACE	U.S. Army Corps of Engineers
WARMF	Watershed Analysis Risk Management Framework

1. INTRODUCTION

1.1 Background and Objectives

The City and County of Honolulu Department of Environmental Services (ENV) is developing a watershed model for the Waikele Watershed as a pilot study for potential use on other Oahu watersheds. The model will be used to prepare planning level analyses for management practices and to assist with future Total Maximum Daily Load (TMDL) regulations. A key water quality component considered in the model is sediment load.

PB Americas and NHC (2010) describe the development, calibration, and some example-planning applications of the pilot WARMF watershed model to the Waikele Watershed. The model was calibrated to measured sediment loads at United States Geological Survey (USGS) gages based on available information about the relative contribution of land and stream-based sediment sources, and the distribution of sediment sources within the watershed. Subsequent studies by the USGS indicated that the contribution of stream-based sources may be less and the land-based contribution may be more than adopted for the pilot model. In order to resolve this issue, ENV funded a geomorphic study of the watershed with the broad goal of understanding the production and delivery of sediment from different erosion processes or sources, the distribution of these processes or sources over the watershed, and the volumes they contribute to streams. The understanding gained from the sediment studies will be used to re-calibrate the watershed model sediment routines. Since the time PB Americas and NHC (2010) was drafted and this study was initiated in 2011, ENV has decided to use an HSPF model of Waikele Stream developed by the State of Hawaii Department of Health (DOH) in coordination with NHC (DOH and NHC, 2010) for watershed modeling rather than WARMF. The process and data requirements for calibrating HSPF and WARMF are similar, so the application of the information gained from this geomorphic assessment will be applied in a similar manner regardless of which watershed model is applied.

To address the above goal, NHC recommended developing a rapid sediment budget from existing studies in the watershed or nearby on Oahu. The estimates of sediment erosion or production from existing studies would then be confirmed or adjusted from the results of existing USGS or other sediment transport measurement programs in the Waikele Watershed.

An earlier memorandum (NHC, 2011) reviewed the studies, publications, and databases that describe erosion, transport, and deposition of sediment in the Waikele Watershed or nearby on Oahu and concluded that the existing information was adequate to develop a rapid sediment budget for the Waikele Watershed. The memorandum also identified important data gaps and suggested methods or approaches to fill these gaps. Some of the materials from this earlier memorandum have been revised and incorporated into this project report but we recommend referring to this memorandum for complete details.

1.2 Sediment Budgets

1.2.1 General Definition

A sediment budget quantitatively describes the volumes of sediment eroded or mobilized on hillslopes, the volumes contributed from hillslopes to streams, the erosion, deposition, and transport of sediment through the stream network, and the volume leaving the watershed. Complete budgets can be very detailed and difficult to prepare. The rapid sediment budget proposed for Waikele Stream will help answer the following questions:

- What are the significant natural and human-induced erosion processes?
- What are the approximate volumes of sediment eroded from hillslopes by each process and what portion of these volumes are contributed to streams? What are the grain size distributions of these sediments?
- What volumes of sediment are eroded from stream banks, bars, and beds? What are the grain size distributions of these sediments?
- What volumes of the total eroded sediments are deposited in streams or on the floodplain? What are the grain size distributions of these sediments?
- What volumes of sediment are transported out of the Waikele Watershed? What are the grain size distributions of these sediments?

1.2.2 Application to Waikele Watershed

We have simplified the development of the Waikele sediment budget with two constraints. First, the budget will be constructed for erosion, transport, and deposition averaged over a reasonably long period that includes the years adopted for the watershed model calibration (1998-2008; WARMF PB Americas and NHC, 2010 and HSPF DOH and NHC, 2010).

Second, the budget will be constructed only for the finest portion of the eroded sediment – silt and clay (grain sizes less than 0.0625 mm) – which form the bulk of the suspended sediment loads measured by the USGS. Once eroded and delivered to a stream, these fine sediments are typically carried through the stream network to the mouth of the watershed. Limiting the budget to these sediments avoids the complex accounting required for coarser sediments which often move slowly through the stream network.

We have further assumed that fine sediment, once mobilized, is carried to the watershed outlet during a storm without deposition. Such an assumption may not be entirely true because some storage may occur within the stream or on the floodplain. (There are no lakes or reservoirs in the Waikele Watershed.) However, deposition is assumed to be minor compared to the total erosion volume and has not been included in the rapid budget.

1.3 Sources of Information

The analyses in this report rely almost entirely on existing information collected by other organizations or on earlier studies prepared for this project:

- Watershed topography, subwatershed boundaries, stream networks, land use, soils, road networks and other information are from earlier studies prepared by PB Americas and NHC (2010) as part of the development of the WARMF model and from studies prepared for the HSPF model developed by the Department of Health (DOH and NHC, 2010).
- Flows, suspended sediment concentrations, and suspended sediment loads were obtained from records published by the USGS or from publications.
- Descriptions of erosion processes, inventories of sources, and methods for estimating long-term sediment production were obtained from various USGS publications for Hawaii and from other published reports and publications.
- Parts of the watershed were visited by helicopter and by vehicle on August 3, 4 and 5, 2011. Travel and access to various sites was arranged by PB Americas, the USGS, and the Department of Environmental Services.

The data provided by others were inspected for consistency but formal check surveys were not completed as part of the project work.

1.4 Direction and Datum Conventions

This report uses the standard convention for naming and referring to the left and right stream banks and floodplains, which is based on an observer facing downstream. We also use standard cardinal directions when referring to the location of various features in the study area (i.e., North, South, East, and West compass points). All specific elevations in this report are referenced to the common Hawaii LOCAL datum.

1.5 Report Organization

The report has been organized so that technical details regarding the sediment budget are included in Appendices and the main results are included in Chapters 2 through 7. The second chapter of the report provides a brief description of the Waikele Watershed and its subwatersheds as they pertain to sediment budgets. It also discusses the stream network and land use databases that are later used in the calculation of erosion. Details are provided in Appendix A.

The third chapter describes the USGS gaging programs in the watershed and defines the fine sediment yields that will be used to adjust or confirm the erosion estimates.

The fourth chapter provides a summary of the erosion processes active in the Waikele Watershed and identifies those processes that are significant to the sediment budget. The fifth chapter describes how the sediment contributions from the significant erosion processes were quantified for the purposes of the rapid sediment budget. Appendix C provides technical details for the calculations.

The final chapters provide the sediment budget for the Waikele Watershed and its subwatersheds, discusses relative contributions of stream and land-based sources, and provide guidance for calibration of the watershed model sediment routines (WARMF or HSPF).

2. WAIKELE WATERSHED

2.1 Introduction

Chapter 2 provides a brief summary of the physical and land use characteristics of the Waikele Watershed that are important in developing a sediment budget. Appendix A provides further details for the individual subwatersheds. PB Americas and NHC (2010) and other publications also provide subwatershed descriptions.

2.2 Watershed Delineation

Waikele Stream flows south across the Schofield and Oahu plains into the West Loch of Pearl Harbor (State Stream Identification No 3-4-10). The upper watershed extends into the eastern slopes of Waianae Range and also into the leeward or western slopes of Koolau Range. The main tributaries from Koolau Range are the Kipapa and Waikakalaua Streams; from the Waianae Range they are the North and South Waikele Stream and Huliwai, Poliwai, Manuwaiahu, and Ekahanui Gulches. The total watershed area of Waikele Stream to the mouth is 48.4 sq. mi (PB Americas and NHC, 2010). For this study, the Waikele Watershed is defined as the area above the Waikele Stream at Waipahu USGS gage (16213000). This gage is on the westbound Farrington Highway Bridge, about 0.6 miles upstream of Pearl Harbor, and has a watershed area of 46.2 sq mi. This watershed area is larger than that quoted by the USGS and was revised based on an improved delineation of stormwater drainage boundaries.

2.3 Subwatersheds

Earlier studies have divided the Waikele Watershed into various numbers of sub-basins. This study is based on the 20 subwatersheds shown on Figure 2.1. Subwatershed outlet points were defined at gaging stations and also set so that individual subwatersheds included areas of similar soils, land use, land ownership, precipitation pattern, or management practices. The 20 subwatersheds were agglomerated into 5 major tributary watersheds for reporting the sediment budget results. These are (Figure 2.1):

1. Waikakalaua Watershed: Subwatersheds 18, 19, and 20
2. Kipapa Watershed: Subwatersheds 11, 12, 13, 14, 15, 16, and 17
3. Upper Waikele Watershed: Subwatersheds 5, 6, 7, and 8
4. Waianae Range Watershed: Subwatersheds 9 and 10
5. Lower Waikele Watershed: Subwatersheds 1, 2, 3, and 4

The sediment budget for the entire watershed will be based on summing the budgets from the 5 major tributary watersheds. Table 2.1 summarizes the watershed area and stream length for the major tributary watersheds.

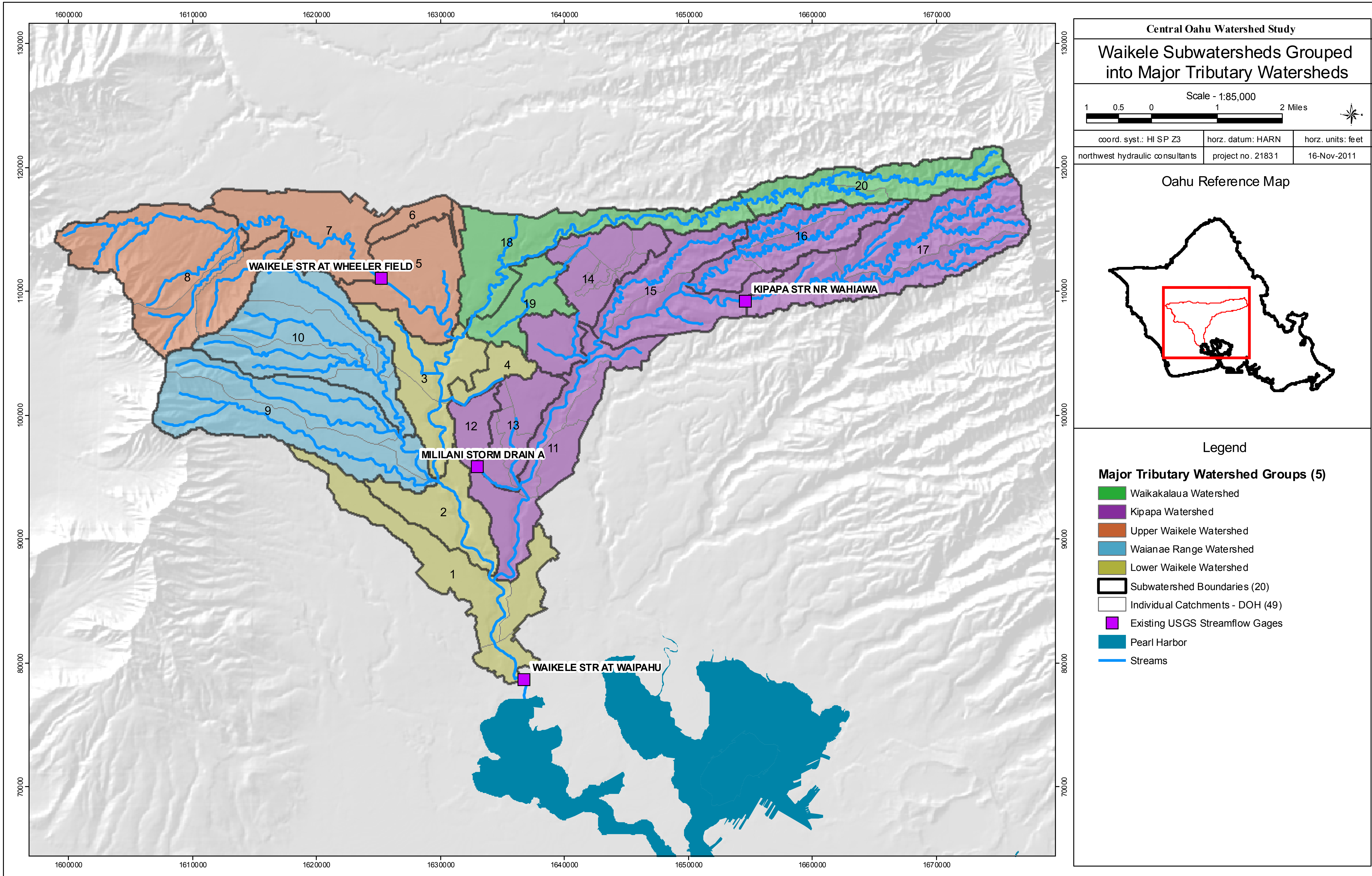
Central Oahu Watershed Study
Waikele Subwatersheds Grouped into Major Tributary Watersheds
Scale - 1:85,000
1 0.5 0 1 2 Miles
coord. syst.: HI SP Z3
horz. datum: HARN
horz. units: feet
northwest hydraulic consultants
project no. 21831
16-Nov-2011
Oahu Reference Map
Legend
Major Tributary Watershed Groups (5)
Waikakalaua Watershed
Kipapa Watershed
Upper Waikele Watershed
Waianae Range Watershed
Lower Waikele Watershed
Subwatershed Boundaries (20)
Individual Catchments - DOH (49)
Existing USGS Streamflow Gages
Pearl Harbor
Streams
WAIKELE STR AT WHEELER FIELD
KIPAPA STR NR WAHIAWA
MILILANI STORM DRAIN A
WAIKELE STR AT WAIPAHU
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Figure 2.1

Table 2.1: Areas and Stream Lengths for the Tributary Watersheds

Watershed No.	Stream Names	Area (square miles)	Stream Length (miles)
1	Waikakalaua	5.8	21.0
2	Kipapa	15.5	52.3
3 and 5	Upper and Lower Waikele	16.5	31.6
4	Waianae Ranges (Ekahanui, Huliwai, Poliwai and Manuwaiahu Gulches)	8.4	26.2
Grand Totals		*46.2*	*131.1*

2.4 Physiography

The Waikele Watershed includes parts of the western (leeward) slopes of the Koolau Ranges, the Schofield and Oahu Plains, and the eastern (windward) slopes of the Waianae Ranges. The Koolau Range and the Schofield and Oahu Plains are formed in Koolau Volcano basalts; the Waianae Range in the older Waianae Volcano basalts (Sherrod *et al,* 2007). Other geologic features include older alluvial and alluvial fan deposits along the eastern side of the Waianae Range that include much of the active agricultural and incised valleys (referred to as “gulches”) along Waikele and Kipapa Stream within the Oahu Plain that are partly filled with recent and older alluvium.

About 60% of the watershed has slopes of less than 20% (11^o) and these are primarily in the Schofield and Oahu Plains. Steep slopes on the plains lie along the walls of the incised Waikele and Kipapa stream valleys (Appendix A). The steepest slopes are in the subwatersheds that extend to the crest of the Koolau Range and, to a lesser extent, the Waianae Range. Average slopes in these watersheds are around 50% (26^o) and up to one-fifth of the area in these subwatersheds lies in the steepest slope class (>80% or 40^o) where landslides commonly occur.

Appendix A describes the soil series observed in the Waikele Watershed. The steep areas of the Koolau and Waianae Ranges are described as “rough mountainous land” and “tropohumults-dystrandets” and little information is available on their characteristics. Soils on the Schofield and Oahu Plains are well described and consist primarily of silty clay Inceptisols, Oxisols, and Utisols (Appendix A).

2.5 Stream Network Classification

The stream network was defined from the GIS databases provided by the State of Hawaii (PB Americas and NHC, 2010). The digital network included the larger tributaries to Waikakalaua, Kipapa, and Waikele streams and Huliwai, Poliwai, Manuwaiahu, and Ekahanui gulches but does not include gullies, zero-order channels, or swales that are visible on large-scale maps or that were observed during field inspections. Average slopes were calculated for stream segments with a minimum length of 1,500 feet and were used to classify the segments into the typology of Montgomery and Buffington (1997), as follows:

- Pool-riffle: bed slope < 0.015
- Plane-bed: 0.015 < bed slope < 0.03
- Step-pool: 0.03 < bed slope < 0.065
- Cascade: 0.065 < bed slope < 0.20
- Colluvial or Hillslope: bed slope >0.20

Figure 2.2 shows the distribution of the stream types in the Waikele Watershed; Appendix A includes long profiles of Waikele and Kipapa streams and the other major tributaries. Pool-riffle and plane-bed types primarily occur on the Oahu and Schofield Plains and in the lower sections of Kipapa and Waikakalaua Streams in the Koolau Range. Step-pool and cascade stream types mostly occur in the upper reaches of the streams in the Waianae and Koolau Ranges (Appendix A). Colluvial stream types occur at the highest elevations in these ranges. The predicted distribution of stream types was roughly confirmed from field reconnaissance from August 3 to 5, 2011 but detailed ground-truthing has not been carried out.

The stream types have different sediment storage and erosion characteristics and the classification was helpful in developing the sediment budget, particularly when transferring erosion observations from one tributary watershed to another.

Colluvial reaches store sediment from hillslopes; stream flows are low and bank and bed erosion are insignificant. Debris flows commonly move the sediment to lower reaches. The cascade and step-pool reaches are dominated by very coarse bed and bank material and only small quantities of fine sediment (silt and clay) are stored in deposits within these reaches. These stream types remain very stable for long periods until very large storms re-mobilize the bed material.

The plane-bed and particularly, pool-riffle stream types are most likely to have lateral channel shifting and bank erosion, and storage of fine sediments on the floodplain or in the stream bed. As a result, these reaches are often the most significant when considering the fine sediment produced by stream erosion. The situation in Waikele Watershed is complex because many of the plane-bed and pool-riffle reaches are in narrow valleys and lateral erosion is often limited or prevented by bedrock valley side walls (Appendix B).

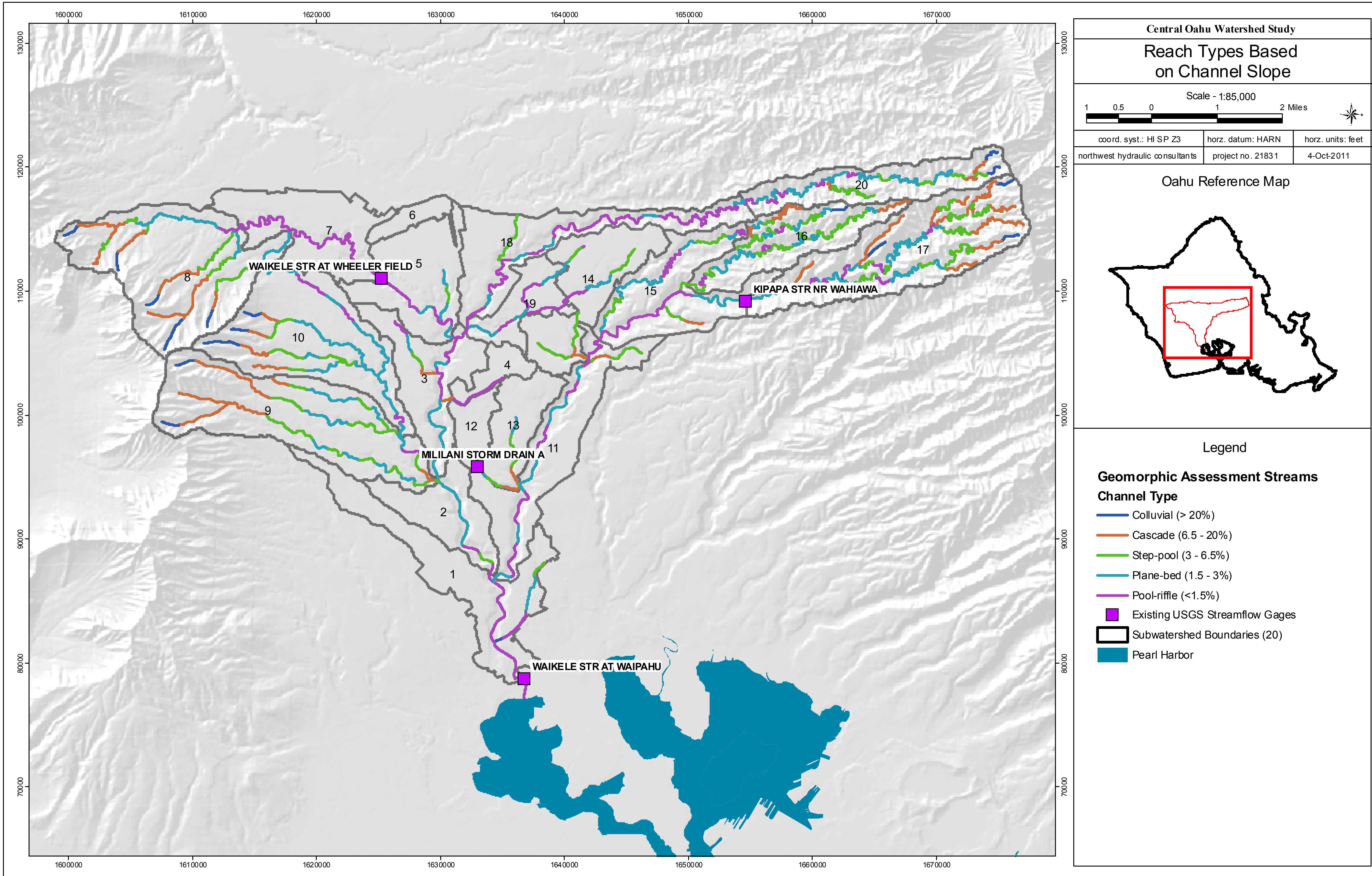
Central Oahu Watershed Study
Reach Types Based on Channel Slope
Scale - 1:85,000
1 0.5 0 1 2 Miles
coord. syst.: HI SP Z3
horz. datum: HARN
horz. units: feet
northwest hydraulic consultants
project no. 21831
4-Oct-2011
Oahu Reference Map
Legend
Geomorphic Assessment Streams
Channel Type
Colluvial (> 20%)
Cascade (6.5 - 20%)
Step-pool (3 - 6.5%)
Plane-bed (1.5 - 3%)
Pool-riffle (<1.5%)
Existing USGS Streamflow Gages
Subwatershed Boundaries (20)
Pearl Harbor
WAIKELE STR AT WHEELER FIELD
KIPAPA STR NR WAHIAWA
MILILANI STORM DRAIN A
WAIKELE STR AT WAIPAHU
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Figure 2.2

2.6 Tributary Watershed Descriptions

The following sections provide a brief description of the major tributary watersheds. Long profiles and summaries of stream types by subwatershed are included in Appendix A. More detailed descriptions are provided in PB Americas and NHC (2010) and Oceanit, Townscape, Inc. and Eugene Dashiell (2007).

2.6.1 Waikakalaua Tributary Watershed

The headwaters of Waikakalaua Stream drain the forested, deeply-dissected, eastern slopes of the Koolau Range near Puukaaumakua Peak. The upper watershed is conservation land and is now undisturbed by human activity. Feral pig wallows have been observed near the stream. Annual precipitation in the upper part of this tributary is the greatest in the Waikele Watershed (>200 in/yr). Stream flow is perennial in the upper watershed.

The stream has a very sinuous course in its upper watershed, formed primarily in bedrock, with narrow floodplains, steep banks, and very coarse bed material (Photos B1 and B2). Below elevations of about 600 feet, Waikakalaua Stream flows through a narrow, steep-sided gulch or valley that has been mostly filled with housing. Sections of the stream have been moved or relocated to accommodate development. The stream appears to be incised, with steep banks, bank protection, and saprolite or bedrock exposed in the bed (Photos B4 and B5). The general appearance during field inspections was of recent bed lowering and bank erosion.

Waikakalaua Stream joins upper Waikele Stream within the Wheeler Air Base at an elevation of about 540 feet (Photo B6). There is little sediment storage at the junction in either stream.

2.6.2 Kipapa Tributary Watershed

The headwaters of the North and South forks of Kipapa Watershed are just south of Waikakalaua Watershed (Photos B7 and B8). The upper watershed is conservation land and is now undisturbed by human activity but plentiful landslides have occurred (Photos B9 and B10). Feral pig wallows have been observed near the stream and on the valley walls. Annual precipitation in the upper part of this tributary is greater than 200 in/yr.

Similar to Waikakalaua Stream, the Kipapa forks have a very sinuous course, formed primarily in bedrock, with narrow floodplains, steep banks, and very coarse bed material (Photo B11 and B12). The individual stream channels are considerably smaller than Waikakalaua Stream. Photos B13, B14, and B15 provide ground-level photos of Kipapa Stream upstream of the USGS gage. Photo B16 provides view up the valley towards the Koolau Range.

Downstream of the USGS stream gage and the junction with the North Fork, Kipapa Stream flows through a prominent gulch or narrow valley incised into the Oahu Plain (Photos B17, B18, B19, and B20). The gulch has a moderately wide bottom and steep side slopes, and the stream is less sinuous than further upstream. Land use consists of urban/residential along the western side of the gulch, agriculture on the eastern side (Photo B20), conservation in the uplands, and forest along the stream banks and tributaries. Patches of crops grow on the bottom of the gulch, primarily banana and papaya.

The bottom of the Kipapa Gulch narrows as it approaches the confluence with Waikele Stream to about 1,000 to 1,500 feet. Large boulders are observed in the stream bed and the banks are lined with trees. The valley bottom is a military reservation. An access road runs along each side of the stream with a bridge crossing about 2 miles upstream of the confluence.

2.6.3 Upper Waikele Tributary Watershed

The headwaters of the upper Waikele Watershed (above the Waikakalaua confluence) are in the Waianae Range. Maximum elevations are about 2,900 feet in the North fork and 2,300 feet in the South fork, on either side of Kolekole Pass. The upper forested slopes are deeply dissected and mostly forested, but with patches of exposed, eroding bedrock (Photo B26). Part of the northern upland area is used by the US Army for training.

The lower part of the tributary watershed is adjacent to the Schofield Barracks and Wheeler Air Field. Military facilities are primarily on the north side of the stream. The lower 5,000 feet of the stream, adjacent to Wheeler Air Field have been straightened. In this reach, the channel is well-incised with steep banks and saprolite exposed in the stream bed near the USGS gage (Photos B24 and B25). Photo B23 shows the upper Waikele Stream at the crossing near Wheeler Stables; Photo B22 shows the mouth at the junction with Waikakalaua Stream and the incision into hard bed materials.

2.6.4 Waianae Range Tributary Watershed

This tributary watershed includes Huliwai, Poliwai, Manuwaiahu, and Ekahanui Gulches. The upper parts of the watershed are in the Waianae Range with maximum elevations of 2,400 to 3,100 feet. The upper watershed is deeply dissected but is maintained as undisturbed conservation land. The lower parts of the tributary watersheds, on the fans formed below the Waianae Range, are prime agricultural land (Photos B27 and B28).

2.6.5 Lower Waikele Watershed

The lower Waikele Watershed consists of that part of the watershed that drains to Waikele Stream downstream of the confluence of upper Waikele and Waikakalaua Streams near Wheeler Air Field, exclusive of the Waianae Range and Kipapa Tributary watersheds. The broad gulch of Waikele Stream is incised well below the Schofield and Oahu plains. The gulch is incised up to 300 feet and the bottom is about 1,500 feet wide. Much of the valley bottom is military reservation and is partly covered with access roads. The Navy’s Lualualei Magazine (Waikele Branch), which was excavated into the steep, bedrock valley walls, is now used for public storage. Downstream of the upper Farrington Highway crossing, Waikele Stream flows in a concrete-lined channel.

Waikele Stream has a wide, shallow boulder-cobble bed through much of this tributary watershed. Banks are lined with tall grass and trees (see Appendix A).

2.7 Current Land Use

Figure 2.3 shows land use in the Waikele Watershed as of 2005; Figure 2.4 shows land use as of 1980 (Appendix A provides details). The three main land uses in 2005 were forest (21.3 sq mi), agriculture (9.1 sq mi), and urban development (9.0 sq mi).

Forested land is the only land use on slopes of the Koolau and Waianae Ranges which are designated and managed as conservation areas. Most of the developed impervious land use is located on the eastern side of the plain, in urban areas such as Mililani Town and Wahiawa. Both the Schofield Barracks and Wheeler AAF military installations contribute developed areas along the northern boundary of the watershed. Agriculture is predominantly located on the western edge of the Oahu Plain near the Waianae Gulches and Waikele Stream. Kipapa Stream has small areas of agriculture along its eastern border.

2.8 Changes in Land Use

The Oahu and Schofield Plains were dedicated to the cultivation of pineapple and sugar cane from the late 1800s to the 1970s. Sugar and pineapple were produced by the Waialua Sugar Company, Del Monte, and Dole Food Co. Since the 1970s, sugar and pineapple cultivation has been greatly reduced, due to a combination of increased international competition and pressure from urbanization.

The Waialua Sugar Company closed in 1996 and Del Monte ceased pineapple operations in 2008; Del Monte's departure left 5,100 acres of leased Campbell Estate land (including areas outside the watershed) lying fallow (Fischer, 2006). The Dole Food Co. is still actively producing pineapple but its operations have decreased in area over the last few years. Much of the plantation land that was previously in sugar cane (and to a lesser extent pineapple) production has been shifted to diversified agriculture or to urban development.

In 1968, Castle & Cooke began the development of Mililani Town, a 3,500 acre low-density suburban community of affordable single-family homes on the Oahu Plain between lower Waikele and lower Kipapa Streams. Since then, the once rural area has been transformed by housing, commercial, and industrial development (Figures 2.3 and 2.4). Urban area has continued to expand, increasing from about 6.2 sq mi in 1980 to about 9.7 sq mi in 2005, including open spaces and golf courses (Appendix A; Figures 2.3 and 2.4).

A comparison of Figures 2.3 and 2.4 shows the expansion of residential and commercial areas at the expense of agriculture. Active agricultural area has declined from about 13.6 sq mi in 1980 to about 9.1 sq mi in 2005 (Appendix A). Figures 2.3 and 2.4 also show shifts in the common crops. By 2005, sugar cane crops had disappeared from the watershed while the area of pineapple production had increased some. New crops, including truck crops and seed corn production, have replaced sugar cane plantations. While not shown on Figure 2.4, the Monsanto Headquarters farm near Kunia Road has also now been converted from pineapple to seed corn production.

El-Swaify (2002) warned that diversified agriculture (truck crops, seed corn, upland taro, onions, etc.) has the potential to deliver much more sediment to streams than pineapple or sugar cane plantations on the same acreage. The increase is largely due to more frequent tillage, soil exposure, and harvest associated with diversified crop operations compared to the plantation crops. As discussed in Appendix C, the different crops in 2005 have resulted in greater sediment production from agriculture despite the smaller area of active agriculture.

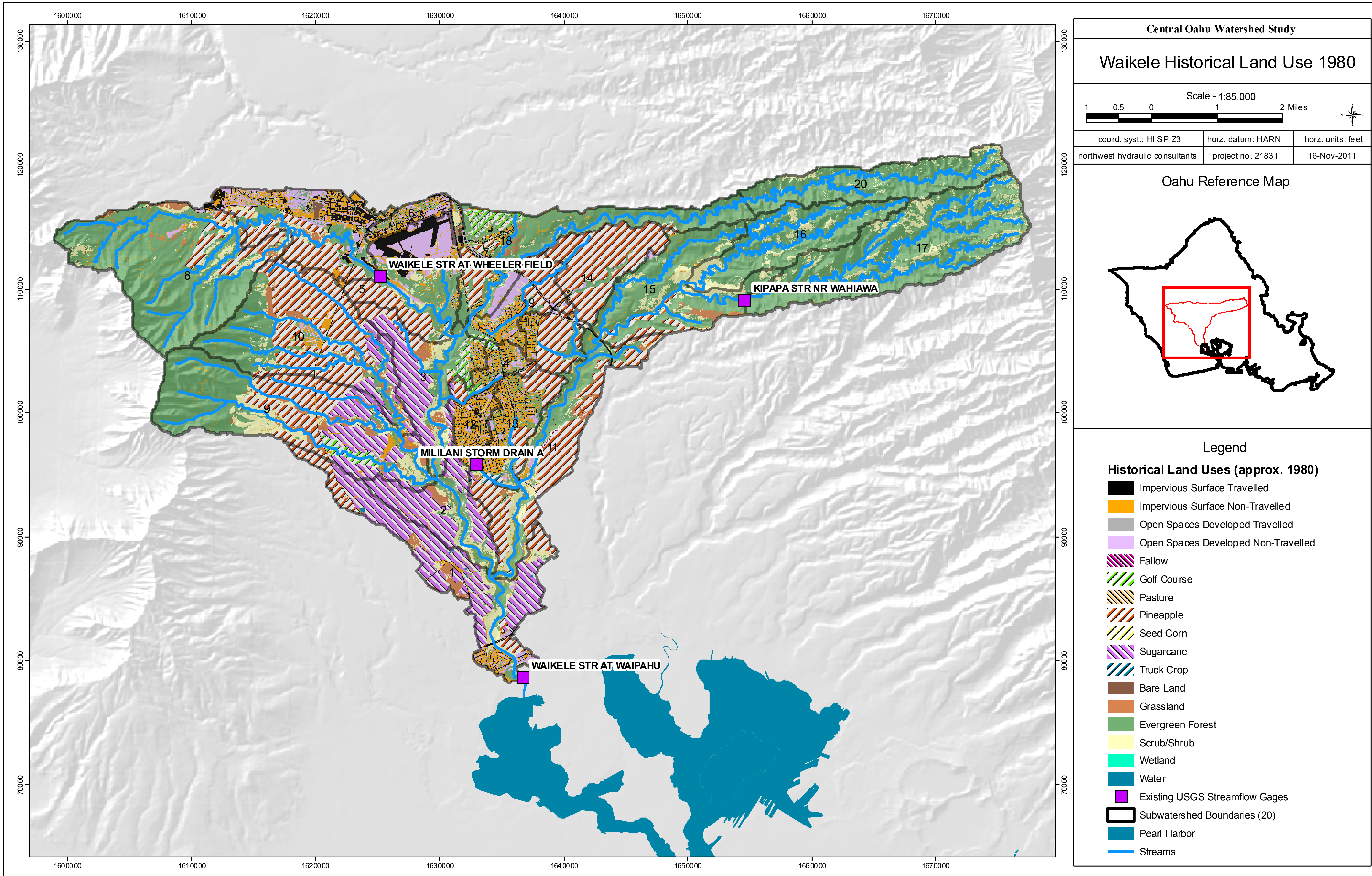
Central Oahu Watershed Study
Waikele Historical Land Use 1980
Scale - 1:85,000
1 0.5 0 1 2 Miles
coord. syst.: HI SP Z3
horz. datum: HARN
horz. units: feet
northwest hydraulic consultants
project no. 21831
16-Nov-2011
Oahu Reference Map
Legend
Historical Land Uses (approx. 1980)
Impervious Surface Travelled
Impervious Surface Non-Travelled
Open Spaces Developed Travelled
Open Spaces Developed Non-Travelled
Fallow
Golf Course
Pasture
Pineapple
Seed Corn
Sugarcane
Truck Crop
Bare Land
Grassland
Evergreen Forest
Scrub/Shrub
Wetland
Water
Existing USGS Streamflow Gages
Subwatershed Boundaries (20)
Pearl Harbor
Streams
WAIKELE STR AT WHEELER FIELD
KIPAPA STR NR WAHIAWA
MILILANI STORM DRAIN A
WAIKELE STR AT WAIPAHU
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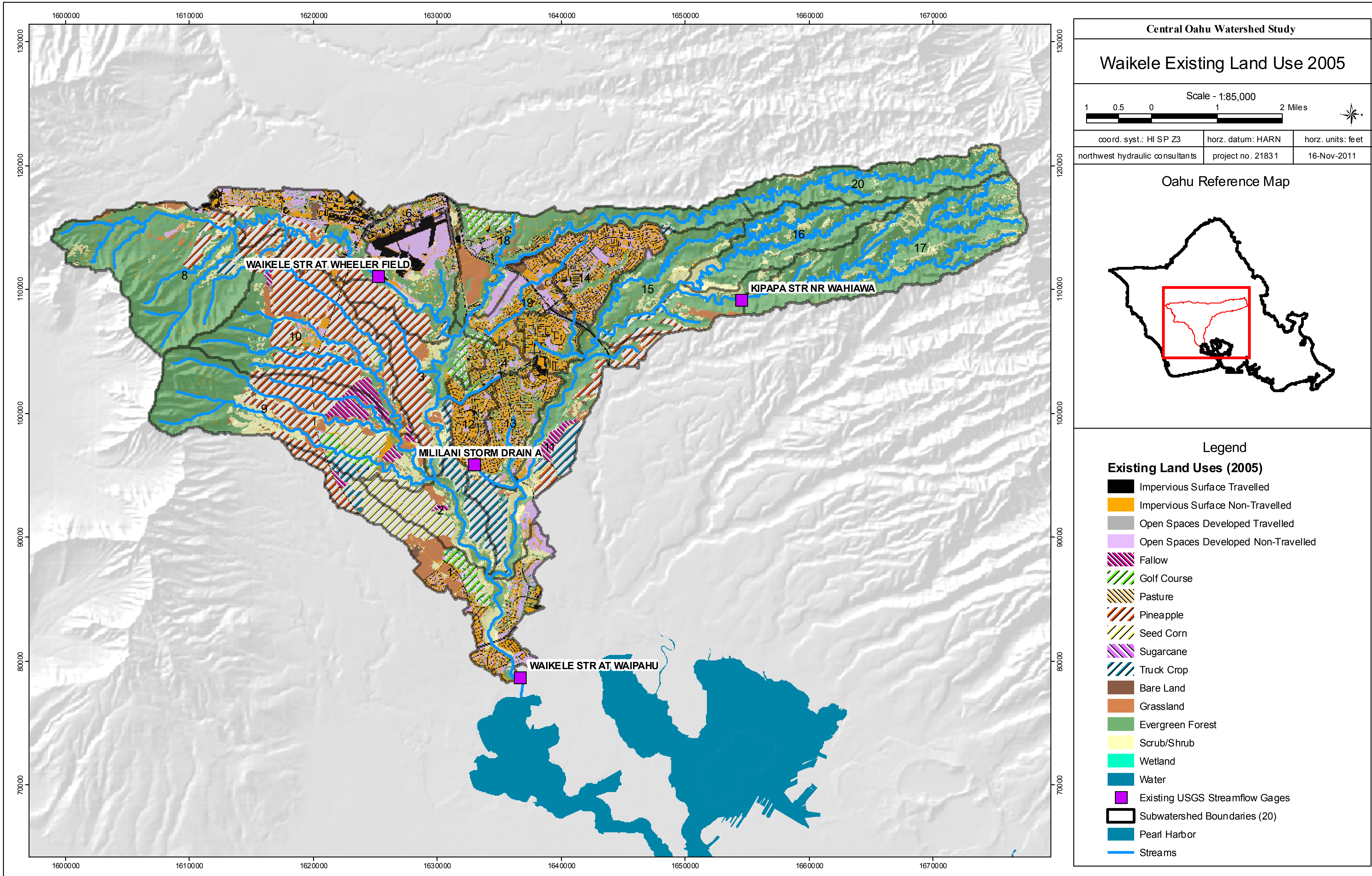
Figure 2.3


Central Oahu Watershed Study
Waikele Existing Land Use 2005
Scale - 1:85,000
1 0.5 0 1 2 Miles
coord. syst.: HI SP Z3
horz. datum: HARN
horz. units: feet
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Existing Land Uses (2005)
Impervious Surface Travelled
Impervious Surface Non-Travelled
Open Spaces Developed Travelled
Open Spaces Developed Non-Travelled
Fallow
Golf Course
Pasture
Pineapple
Seed Corn
Sugarcane
Truck Crop
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WAIKELE STR AT WHEELER FIELD
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WAIKELE STR AT WAIPAHU
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Figure 2.4

3. SEDIMENT TRANSPORT

3.1 Introduction

Estimates of sediment transport from the watersheds, averaged over various time periods, are required to confirm or adjust the estimates of erosion from hillslopes and streams. These estimates of average transport will be compared to average erosion estimates from their watersheds and the various parameters that were adopted to calculate erosion from the various sources will be adjusted as appropriate (see Chapter 5).

This chapter describes the sediment gaging programs in the Waikele Watershed, discusses annual loads and the seasonal and daily variation of sediment loads, and provides annual fine sediment loads for the gaging stations averaged over several periods.

3.2 Fluvial Sediment Transport

Figure 3.1 illustrates the nomenclature adopted for sediment transport and bed sediment layers. The total sediment load carried by a stream can be divided, based on the mode of transport, into suspended and bed loads (left side of Figure 3.1). The suspended load consists of clay and silt sized sediment maintained in suspension by turbulence, with sand suspended during high flows when turbulence is greatest. Bed load consists of the coarser particles transported along the bed by rolling, sliding, or saltating. The boundary between the size of particles moved in suspension or as bed load is not precise and varies with the flow strength; the greater the flow at a site, generally the coarser the sediment that can be suspended by turbulence.

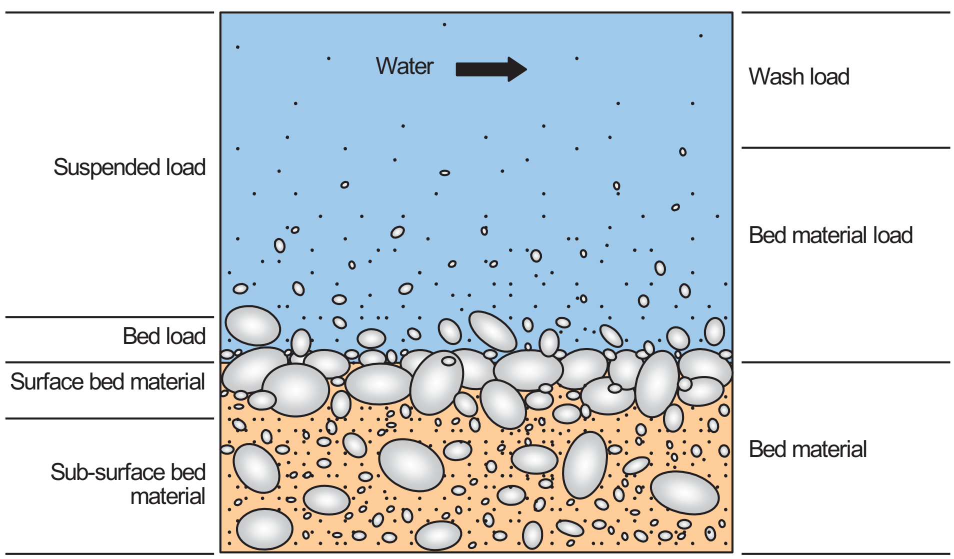

Figure 3.1: Sediment Transport and Bed Material Definitions

The total sediment load can also be divided by its presence in the streambed into bed material and wash loads (right side of Figure 3.1). Particles that are found in significant quantities in the bed and are exchanged with the bed load during transport are part of the bed material load. The wash load consists of fine sediments (usually silt and clay) that are continuously maintained in suspension and, thus, are not found in the bed in significant quantities. The wash load is determined by supply and it may be somewhat independent of water discharge. Typically, it is measured as part of suspended-sediment gaging programs.

Bed load transport occurs when the stresses or velocities imposed by the flow exceed the critical stress or velocity for the threshold of movement for the surface bed material. The coarse beds that are observed on streams in the Waikele Watershed typically have a surface armor layer that is void of fine sediments (silt, clay, and fine sand); any fine sediments are stored in the sub-surface bed material (Figure 3.1). Erosion and transport of the fine sediments in the sub-surface layer only occurs after the coarser surface bed material is mobilized. This occurs infrequently in most coarse bed streams and, as a result, the bed only infrequently contributes wash load or suspended size sediments. The volume of silt and clay stored in alluvial sub-surface bed material is typically only 1 to 2% of the total weight, although the total wash load may be increased by attrition of larger particles while they are transport.

Sediment transport, particularly as bed load, can result in abrasion that produces finer sediments by breakdown of coarser ones (referred to as “attrition”). The volume of fine sediment produced by this process will depend on the geology or nature of the sediments and on the distances that they travel. Hill et al (1988) identified this process as an important contributor to the fine sediment budget in North Halawa Stream because deep chemical weathering results in coarse clasts composed of secondary minerals that break down rapidly. This process can be incorporated in the sediment budget by increasing the observed fine sediment content of the erosion source material to account for breakdown of the coarse fraction, or by specifically calculating attrition as a component of the sediment in transport.

3.3 Definitions of Sediment Terms

Some of the terms that are commonly used in this chapter are defined below:

- Suspended sediment concentration: The dry weight of sediment in a given volume of water, expressed as milligrams/liter (mg/L). The quoted USGS concentrations represent the average concentration over the stream cross section rather than the concentration of an individual grab sample.
- Suspended sediment discharge or load: The weight of suspended sediment carried past a point as calculated from the suspended sediment concentration and the water discharge. The USGS publishes daily and annual loads as tons/day. The weight of

sediment transported past a point in a year is the annual load multiplied by 365 and is expressed in tons or tons/year.

- Fine sediment discharge or load: That portion of the suspended sediment load that consists of silt and clay (particle diameters less than 62.5 microns) is the fine sediment discharge. This portion varies with flow but silt and clay compose most of the suspended load in Hawaii.
- Fine Sediment Yield: The total weight of sediment delivered to a point in the watershed averaged over a number of years and often expressed per unit area of watershed, as tons per mi^2.
- Denudation Rate: Denudation is the long-term lowering of the elevation of the earth's surface from weathering and erosion. In this report, the denudation rate is the average annual lowering of the watershed surface and is expressed in inches (in) or millimeters (mm). The denudation rate is calculated from the sediment yield, with appropriate adjustments for the bulk density of eroded sediments.

3.4 Sediment Gaging Programs

Almost all of the suspended sediment discharge measurements in the Waikele Watershed have been collected by the USGS and are available on their website. A few earlier measurements are reported in Jones *et al* (1971) and Doty *et al* (1982) and there may be some others in some of the older reports that they cite. PB Americas and NHC (2010) list total suspended solids (TSS) data collected as part of water quality measurements.

The USGS has collected and published daily suspended sediment discharge measurements at four gaging stations in the Waikele Watershed, as part of routine monitoring and as part of the cooperative Suspended-Sediment Monitoring for Waikele Watershed that began in 2007 and ended in 2010 (USGS, 2011). Stations are described in Table 3.1.

Table 3.1: USGS Suspended Sediment Discharge Records in Waikele Watershed

Gage Name	Number	Area (mi^2)	Period of Record (water year)	
			Water Discharge	Sediment Discharge
Waikele Stream at Waipahu [1]	16213000	46.2	1953-2010	1973-92; 2008-10
Waikele Stream at Wheeler Field	16212601	6.72	2008-10 (peaks 1958-2010)	2008-10
Kipapa Stream near Wahiawa	16212800	4.28	1958-2010	1974-81; 2008-10
Mililani Storm Drain A at Mililani [1]	212604158 012700	0.56	2008-10	2008-10

1. Watershed area from PB Americas and NHC (2010); Mililani Storm Drain not quoted by USGS.

Sediment discharges at the stations on Waikele and Kipapa Streams have not been measured continuously between 1973 and 2010; on the other hand, flow records have been continuous. Sediment rating curves were developed from reported measurements and used to estimate sediment discharges at Waikele and Kipapa gages for those years when they were not recorded (see following section).

3.5 Annual Suspended Sediment Loads

The USGS reports annual suspended sediment loads for the Waikele Watershed and other gages on Oahu as part of routine monitoring and as part of sediment studies. All these data provide a useful context for the Waikele measurement program. Results from the published reports are discussed in the following sections; references follow the main text.

3.5.1 Measured Annual Yields on Oahu

Table 3.2 provides average annual suspended sediment yields measured at the stations in the Waikele Watershed, at selected stations on the leeside of the Koolau Range with reasonable lengths of record (five years or more) and from sedimentation studies carried out on Oahu. The average annual yields are expressed in tons per square mile per day in order to compare watersheds of different areas and are quoted for two periods and for the total length of record.

Table 3.2: Annual Suspended Sediment Yields for Various Sites or Stations

Site or Station	Gage #/Source	Average Annual Yield (tons per day/mi^2)			
		2008-2010	1974-1981	Circular 33 [1]	Period of Record
Waikele at Waipahu	16213000	5.0	1.70	1.9	1.95
Waikele at Wheeler Field	16212601	1.08	n/a	n/a	n/a
Kipapa near Wahiawa	16212800	1.06	2.65	1.8	2.48
Mililani Storm Drain A	212604158 012700	0.07	n/a	n/a	n/a
N Halawa near Honolulu	16226200	1.07	n/a	n/a	2.75
N Halawa near Kaneohe	16225800	n/a	n/a	n/a	2.38
N Halawa near Halawa	16226400	0.77	n/a	n/a	n/a
Moanalua near Kaneohe	16227500	n/a	n/a	n/a	0.43
Kalihi near Honolulu	16229000; Doty et (1982)	n/a	n/a	n/a	0.44

Sedimentation in Ali Wai Canal, Honolulu	McMurty *et al* (1995)	n/a	n/a	n/a	0.47
Waimaluhia Reservoir, Oahu (1983-98)	Wong (2001)	n/a	n/a	n/a	1.55

1. Jones et al (1971) based on application of suspended sediment rating curves to flow duration during the 1950s and 1960s. Suspended sediment rating curves based on few measurements at moderate flows

It is difficult to compare the average loads from the different stations because most of the records are short, the stations have different periods of record, and some records do and some do not include measurements during extreme floods. However, Table 3.2 suggests that the measured annual suspended loads in Waikele Watershed are higher than at other stations on the leeside of Koolau Range with the exception of North Halawa Stream. The records from Halawa Stream (and also Waimaluhia Reservoir on the windward side) include significant volumes of sediments generated by construction of the H-3 Highway and thus over-estimate their typical long-term loads. Hill *et al* (1998) and Wong and Yeatts (2002) provide estimates of the contributions of construction to the total loads in North Halawa Watershed.

3.5.2 Waikele Annual Loads

Figure 3.2 plots annual flow versus annual suspended sediment load for the 23 years of record at the Waikele Stream at Waipahu gage. When annual flows are less than about 25 cfs, annual sediment loads are typically less than 20 ton/day (7,300 tons). The figure also shows a general trend of increasing annual loads with annual flows. Within this broad trend, the WY 2009 suspended sediment load is an extreme outlier for the observed flow that year. The figure also shows an apparent trend to lower annual sediment loads for the same annual flows since about 1982.

Figure 3.3 plots annual suspended sediment load versus peak flow for the same years of record. This plot provides a better fit with the annual suspended loads. As discussed below, this occurs because most of the annual sediment load is transported during the annual peak flow.

The regression equation between Q_s (annual sediment load in tons/day) and Q_p (annual peak flow in cfs) for the Waikele gage is:

$$Q_s = 0.000485 * Q_p^{1.38} \quad (N=23)$$

The regression equation for the Kipapa Stream at Wahiawa gage is:

$$Q_s = 0.000074 * Q_p^{1.49} \quad (N=11)$$

These two equations provide one approach to fill missing years in the Waikele and Kipapa sediment gaging records between 1973 and 2010. As discussed earlier, rating curves based on measured daily water and sediment discharges were also developed at the two gages and they were used to estimate sediment discharges on those days when sediment measurements were not made. Bias was removed with a smearing estimator (Duan, 1983) and the averages calculated from filling with the regression from the daily observations are reported in Section 3.9.

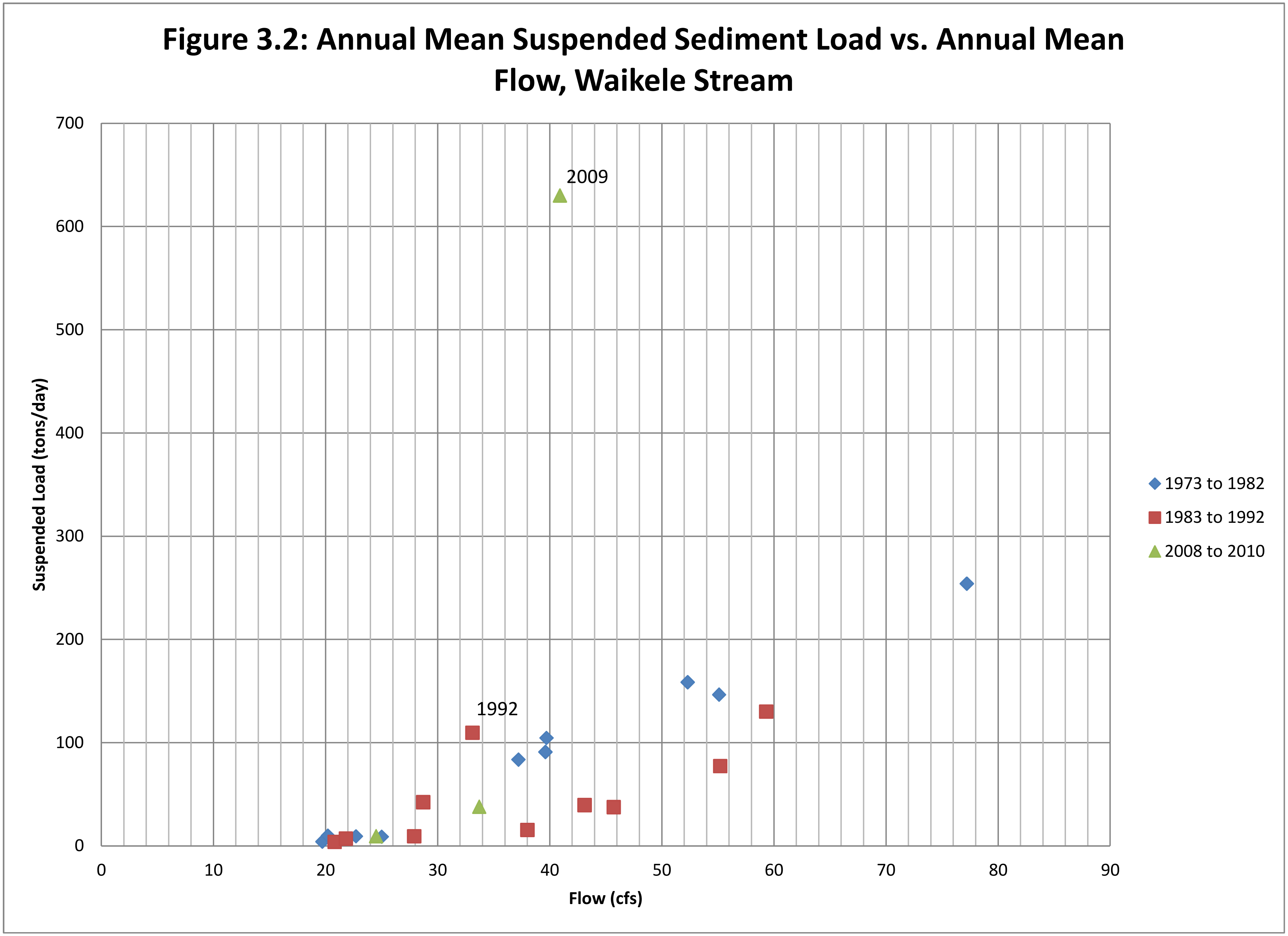
Figure 3.2: Annual Mean Suspended Sediment Load vs. Annual Mean Flow, Waikele Stream
Suspended Load (tons/day)
Flow (cfs)
0
100
200
300
400
500
600
700
0
10
20
30
40
50
60
70
80
90
2009
1992
1973 to 1982
1983 to 1992
2008 to 2010

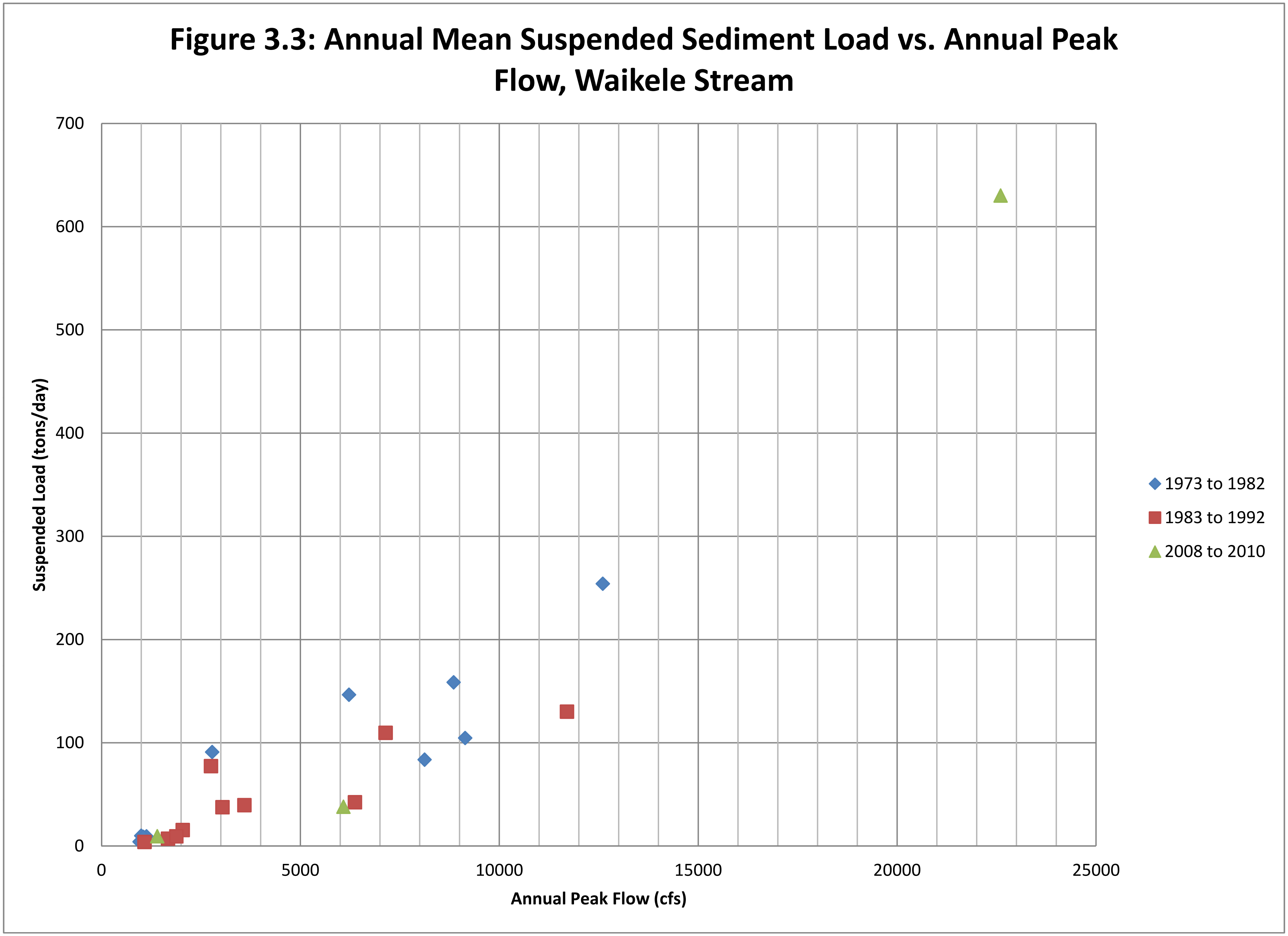
Figure 3.3: Annual Mean Suspended Sediment Load vs. Annual Peak Flow, Waikele Stream
Suspended Load (tons/day)
700
600
500
400
300
200
100
0
0
5000
10000
15000
20000
25000
Annual Peak Flow (cfs)
1973 to 1982
1983 to 1992
2008 to 2010

3.6 General Observations on Sediment Transport

3.6.1 Waikele Watershed

Comparison of the overlapping records at the four sediment gaging stations in the watershed provides some useful observations on erosion. It suggests that over moderately long time periods, the Kipapa subwatershed, and possibly other subwatersheds in the Koolau Range, has a higher annual yield per unit area, and consequently greater erosion, than the overall watershed as measured at the Waikele Stream gage.

Less is known of the relationship between sediment yields from the subwatersheds draining the Waianae Range and the overall watershed. Table 3.2 indicates that over the past few years, the annual yield per unit area at the upper Waikele gage has been similar to those at the Kipapa and North Halawa gages. The Mililani Storm Drain A at Mililani gage measures sediment yield from a residential area and the observed yield confirms the general observation that erosion from mature residential areas is not a very important source of sediment.

Over short periods, the yield per unit area from the overall watershed may be much greater than from Kipapa (or another) subwatershed, depending on the distribution of intense storm rainfall over the watershed. During the 2008-2010 water years, the sediment yield at the mouth was about four to five times greater than in the upper Waikele or Kipapa Streams (Table 3.2). This is discussed further in Section 3.7.

Doty *et al* (1982) indicated that annual suspended sediment concentrations were less than 10 mg/L at most stations on Oahu but often exceeded 20 mg/L at the Waikele Stream at Waipahu gage in the 1970s. Review of USGS records showed that daily suspended sediment concentrations averaged 45 mg/L at the Waikele gage and 22 mg/L at the Kipapa gage over their two periods of sediment gaging.

3.6.2 Seasonal Variation of Transport

Inspection of the mean of monthly sediment discharges shows that most of the annual sediment load is transported during storms that occur between December and March, with very little load transported from May through August.

3.6.3 Daily Variation of Transport

Inspection of the daily water and sediment discharges recorded at the Waikele Stream at Waipahu gage indicates that most of the annual suspended sediment load is transported during annual peak flows. Histograms of daily sediment transport for the period of record at stations on Oahu (USGS, 2007) show that much of the annual load is transported in less than 1% of each year (3 days) and nearly all the annual load is transported in less than 10% (30 days) of the year. Doty *et al* (1982) observed similar results in their earlier study.

At the Waikele at Waipahu gage, annual histograms show that between 70 and 100% of the suspended sediment load is transported in less than 1% of the days each year and more than 95% is transported in less than 10% of the days each year. About half of the total load over the period of record is transported in the 25 days with the highest flows.

3.7 December 11, 2008 Flood

In the 2009 water year, the Waikele at Waipahu gage had a record peak flow of 22,600 cfs on December 11, 2008. This peak was nearly twice as large as the previous largest recorded peak. The annual suspended load for the 2009 water year was also more than twice as great as the next largest annual load. The 2009 annual load represented about 30% of the total suspended sediment transported over the 23-year period of sediment discharge record and was equivalent to about 8 years of average transport.

The sediment gage was damaged during the flood and sediment loads were estimated by extrapolating the previously observed instantaneous flow-concentration curve. As such, there is greater uncertainty than usual in the measured sediment transport during this flood.

On this same date, the peak flow at the Kipapa near Wahiawa gage was the 11th highest in the period of record; at the Waikele at Wheeler Field gage, it was the 3rd highest of record. Daily loads were not unusually high. Table 3.3 provides a summary of daily sediment loads at the various USGS stations and the interpolated load from the rest of the watershed for the December 11, 2008 flood.

Table 3.3: Suspended Sediment Discharge during December 11, 2008 Flood

Station	Name	Area (mi^2)	12-11-08 Load (tons)	Yield ($tons/mi^2$)
16212800	Kipapa near Wahiawa	4.28	2,350	550
16212601	Waikele at Wheeler Field	6.72	6,600	980
-	Remainder of watershed	34.7	218,050	6,300
16213000	Waikele at Waipahu	46.2	227,000[e]	4,900

Assuming that daily sediment loads from Waikakalaua Stream were similar to those from Kipapa Stream and that sediment loads from the upper tributaries in the Waianae Range were similar to those from the upper Waikele Watershed, it appears that the vast majority of the suspended sediment discharged during the December 11 flood was eroded from the Oahu or Schofield Plain rather than from the Koolau or Waianae Ranges. If converted to a denudation rate, the sediment discharge from the remainder of the watershed is equivalent to an average lowering of the land surface of about 1.5 mm, assuming an average bulk density of 87 lb/ft^3, for the eroded soils

3.8 Suspended Fine Sediment Loads

A breakdown of the annual suspended loads into grain size classes (clay, silt, and sand) has not been published for any of the Waikele sediment stations. Grain size distributions have been prepared for a few of the suspended sediment samples and could be used to adjust the reported suspended sediment loads to fine sediment (clay and silt) loads. However, the results of a more detailed study in North Halawa stream have been used instead. Here, Hill *et al* (1998) reported that the 1991 and 1992 annual suspended loads were 85% and 87% silt and clay. We have adopted an average of 86% silt and clay to adjust observed suspended sediment loads or yields to fine sediment loads or yields in the Waikele Watershed.

3.9 Average Annual Fine Sediment Yields

Table 3.4 summarizes average annual fine sediment yields (AFSY) over various time periods at the Waikele and Kipapa gages. These were calculated by filling the record of daily suspended sediment loads at the two gages, as discussed earlier, and by converting to fine sediment as described in the previous section.

Table 3.4: Average Annual Fine Sediment Yields over Various Time Periods

Time Period	Average Annual Fine Sediment Yields in various units		
	(tons/day)	(tons)	Denudation (mm)[2]
Waikele at Waipahu (16213000)			
1973 to 2010	73.4	26,800	0.16
1998 to 2008	32.8	12,000	0.07
Period of record	75.6	28,600	0.16
Kipapa near Wahiawa (16212800) [1]			
1973 to 2010	10.1	3,700	0.23
1998 to 2008	3.4	1,200	0.08
Period of record	8.2	3,000	0.19

1. The Kipapa gage did not operate during the 2005 to 2007 water years and annual loads were not estimated for these years
2. Denudation rates are based on the total suspended load and a soil bulk density of 94 lbs/ft^3

As indicated by the values in Table 3.4, the WARMF calibration years (1998 to 2008) appear to have had an unusually low suspended sediment yield in the Waikele Watershed when compared to longer periods, primarily as a result of low to moderate flood peaks at the gage. We have adopted the AFSY over the 1973 to 2010 period as a suitable average for comparison with the average yields calculated from erosion processes.

It is interesting to compare the yields and denudation rates calculated for the two gages for the 1973 to 2010 period. Table 3.4 suggests that long-term erosion or lowering of the land surface proceeds at about a 40% greater rate in Kipapa Watershed than for the watershed as a whole.

Less is known of erosion rates in the Waianae Range but they are assumed to be lower because of the much lower annual rainfall, the different geology of the basalts, and the greater age and smaller areas of steep lands.

It is also interesting to compare the calculated denudation rates to the long-term denudation rate of 0.1 mm that has been estimated for Oahu since the Pliocene (see Moberly, 1963; Ellen *et al,* 1993). Denudation rates in the Waikele Watershed have been based on soil bulk densities rather than the density of bedrock and thus may not be a suitable comparison to the above rate. If they are, denudation in the Waikele Watershed is currently proceeding at a rate that is about 60% greater than the long-term background rate, likely as a result of various human disturbances, but possibly as a result of unusual weather over the past 40 years.

4. SEDIMENT SOURCES

4.1 Erosion Processes

Based on previous studies in the Waikele Watershed and nearby areas on Oahu (see various documents in References section), sediment is mostly eroded by processes that fall into the following four broad categories:

- Landslides or Slope Failures
- Slow-moving (Deep-seated) Landslides and Creep
- Stream Erosion
- Surface Erosion

The relative contributions by the different processes to the total volume eroded in a subwatershed will vary with precipitation, soil, topography, and land use. In general, landslides will be most important in the steep, wet subwatersheds in the upper elevations of the Koolau Range, such as Subwatersheds No. 14, 15, 16, 17, and 20 (Figure 2.1). Surface erosion from agricultural, military, and urban land uses and stream erosion will be the dominant processes in the low-relief, human-modified subwatersheds on the Oahu Plain.

This chapter provides a brief description of the erosion processes; Chapter 5 describes the methods used to quantify their contributions to the sediment budget. An earlier technical memorandum (NHC, 2011) described the processes in more detail, provided a summary of previous studies in the Waikele Watershed and on Oahu, and identified their application to the Waikele sediment budget.

4.2 Landslides or Slope Failures

There is a long history of research on shallow slope failures on Oahu. Wentworth (1943; also White, 1949) described soil avalanches on the leeward side of the Koolau Range, estimated their frequency of occurrence, average size, and total eroded volume, and calculated a preliminary denudation rate for this process. In the 1980s and 1990s, the USGS prepared landslide hazard studies for the Honolulu District based on an inventory of landslides from air photos taken between 1940 and 1989, including the 1987-88 New Year's Eve storm. In the 1990s and 2000s, the USGS prepared a sediment budget and other sediment studies in the Koolau Range as part of evaluating impacts of construction of the H3 Highway.

Peterson *et al* (1993) categorized the slope failures as deep-seated landslides, saprolite landslides, and "soil slip/debris flows" (also called debris slides and flows). The deep-seated landslides are discussed in Section 4.3. They observed a few saprolite landslides but the vast majority of the slope failures were debris slides/flows. Debris slides/ flows and saprolite landslides are triggered by severe storms and may also be triggered by earthquakes. A few failures occur on the leeward slopes of the Koolau Range in most years; however, abundant failures only occur infrequently, during extreme rains (Wilson, Torika and Ellen, 1992).

The saprolite landslides initiate in weathered bedrock (saprolite) and are usually much deeper or thicker than debris slides. These landslides are relatively uncommon but the depth of material mobilized by the slide can be up to 17 feet and they can move very large volumes of debris. A total of 35,000 m^3 was moved by one landslide in Kupaua Valley (Peterson *et al,* 1993).

Debris slides (soil slips) initiate on steep slopes, often as a shallow slab of soil and vegetation sliding over weathered bedrock or a low strength layer in the soil. The slides usually occurred on slopes of more than 20^o and most commonly on slopes of 40^o to 50^o. The slides often initiated or turned into debris flows, which are saturated or supersaturated flows of water and soil (Varnes, 1976). The slides/flows then travel from a few tens of feet to thousands of feet, generally down a steep drainage channel. The larger flows incorporate soil and organic debris from the bottom and sides of gullies and stream channels, thus increasing their volumes.

4.3 Slow-Moving Landslides and Creep

Baum *et al* (1989) and Baum and Reid (1992) describe deep-seated landslides near Honolulu. A review of these publications suggests that these slow-moving landslides are of little significance to the sediment budgets proposed for this study. On the other hand, creep, which is the very slow downslope movement of soil and debris under gravity, may be an important erosion process on steep slopes in the upper Waikele Watershed.

Creep is a chronic process that occurs on most slopes. Generally, rates are too slow to perceive and they are calculated as an average over a period of years or decades by measuring the downslope displacement of the soil column. Creep contributions to the sediment budget are likely to be most significant in confined valleys where steep, colluvial aprons form on lower slopes adjacent to the stream. Creep moves soil material towards the stream but it may enter as a result of bank erosion or small slides along the toe of the colluvial slopes that occur during floods.

4.4 Stream Erosion

Stream erosion includes both the lateral retreat of stream banks and the vertical incision of the streambed. Lateral or bank erosion occurs primarily during high flows, although saturation of banks may result in their failure during low and moderate flows. Erosion and bank retreat result from detachment and removal of soil particles by flowing water or from toe erosion, over-steepening, and subsequent failure or collapse of banks. Bank erosion is usually greatest on bends or where high flows are directed at a bank. Instream works, bank alterations, removal

of riparian vegetation, land use on top of the bank, or channel incision (see below) may all increase bank erosion rates.
Bank heights are fairly easily defined where the stream has an active floodplain. Where streams are incised well below their floodplain or where they are confined by valley walls or other deposits, bank heights are less well-defined and are often assumed to be about the same as the water depth at some specified return period flood.

Bed incision, or degradation, refers to the removal of streambed materials as part of a long-term adjustment towards some equilibrium gradient or to a lower base level. Scour refers to the bed adjustments that occur during a flood. Incision often results from lowering of downstream gradient controls or changes to peak flows, the supply of coarse sediment to a 3reach, or such factors as stream roughness (Galay, 1983). Past incision or degradation is often indicated by “knickpoints” or steps in the bed profile that mark the present upstream limit of bed lowering.

Existing studies show that bed material is coarse throughout most of the Waikele Watershed (PB Americas and NHC, 2010). The percentage of fine sediments (silt and clay) in these materials is expected to be very low and incision is unlikely to provide a substantial contribution to the sediment budget unless it is very rapid and extensive and considerable attrition occurs during transport.

4.5 Surface Erosion

Surface erosion includes dry ravel, rain splash, and sheet and rill erosion. Dry ravel refers to particle detachment under gravity; splash, sheet and rill erosion refer to the detachment and transport of individual soil particles by overland flow. Dry ravel has not been considered a significant sediment source in previous studies and it is not considered further in this study.

In the Waikele Watershed, overland flow and surface erosion are thought to be relatively rare on undisturbed, forested soils, despite their fine texture, and significant surface erosion will be confined to sites where vegetation has been removed and soils are exposed, or where soils are disturbed or compacted (PB Americas and NHC, 2010). Overland flow will also occur where bedrock is exposed and in urban (residential and commercial) areas but flow from these sources is expected to result in little or no soil erosion. Surface or sheetwash erosion is chronic, occurring during rainstorms throughout the year, occurring at many sites, and often leaving little evidence that it has occurred, particularly where rills or other erosion features are removed by tillage or other human activities.

Natural vegetation and soil disturbance, followed by surface erosion, occur on landslide scars, fire-damaged slopes (some fires may be human-caused) and trails formed by feral pigs, goats, or other wild animals. PB Americas and NHC (2010; and references therein) suggest that damage to vegetation by feral pigs may be a component of the sediment budget in the conservation lands in the Koolau Range. A recent study by Dunkell *et al* (2011) examined potential erosion consequences by comparing sediment yield from plots where pigs are excluded and where they are not.

Disturbance of vegetation and soil by human activities, followed by surface erosion, occur on military reservations and training lands, construction sites, agricultural fields, range lands, roads, and urban development. Disturbance and surface erosion may be short-term, such as at construction sites, or chronic, such as from agricultural fields.

The portion of the sediment eroded by sheetwash that is delivered to streams during a storm is often difficult to establish, particularly in low relief or relatively flat subwatersheds – shallow slopes, berms, vegetative buffers, or obstructions may result in re-deposition of the eroded material before it enters streams. In steep, upper subwatersheds, the majority of sediment eroded by sheetwash is delivered to streams.

4.6 Summary

Literature review and field reconnaissance suggest that the following erosion processes will make significant contributions to the sediment budget in at least some of the subwatersheds:

- Soil slips/flows
- Saprolite landslides
- Soil creep
- Stream bank erosion
- Sheetwash erosion from soils in conservation areas exposed by landsliding, fire, or feral animals
- Sheetwash erosion from soils exposed by agriculture, roads (particularly native soil surfaced roads), urban areas, and military training areas

Bed incision or degradation is thought to be a minor component of the long-term sediment budget in the Waikele Watershed. Floods that mobilize bed material will result in erosion of fine sediments from the subsurface bed material; however, when the bed re-forms, fine sediment will be trapped in the subsurface sediments or will filter into the subsurface during subsequent small floods and there will be little net erosion from this source. As noted earlier, stream incision may result in net erosion of fine sediment from the bed, but it is unclear if incision is proceeding and the net fine sediment yield from this source is expected to be relatively insignificant.

5. QUANTIFYING SEDIMENT SOURCES

5.1 Introduction

This chapter provides an overview of how the contributions of fine sediment to streams by the significant erosion processes in the Waikele Watershed were calculated. Appendix C provides details for the various significant erosion processes.

Yields were generally calculated from empirical relationships between precipitation, land surface or land use characteristics, and erosion rates for a particular process, and then adjusted to fine sediment yields based on the particular soil conditions for the erosion process in the Waikele Watershed. Empirical relationships developed from studies in the Waikele Watershed or on Oahu were used for the calculations when they were available (refer to NHC, 2011). When they were not available, other commonly accepted relationships were substituted. Table 5.1 provides a summary of calculation methods for the different components of the sediment budget.

The following subsection discusses sources of information on soil characteristics. The remaining subsections describe the general approach to calculation of the volume or weight of sediment eroded by each of the significant erosion processes.

5.2 Soil Characteristics and Fine Sediment Yield

The quantities of fine sediment contributed to streams by the various erosion processes depend on the volume of sediment eroded, the bulk density of the soil, the percentage of clay and silt in the eroded soils, and attrition during transport that may increase the volume of clay and silt through breakdown of coarser particles.

5.2.1 Fine Sediment Percentages

The gradation of soils and the percentage of fine sediments in the Waikele Watershed are defined in the SURGO database. Unfortunately, there are no descriptions of the soils in the upper elevations of the Koolau Range where landsliding occurs, and no descriptions of the fluvial bank deposits along many of the streams, particularly the upper elevation step-pool and cascade stream types, that are exposed to bank erosion and soil creep.

Where suitable information is available, the percent fine sediment of eroded soils was defined from the soils databases. Where such information is not available, it was defined from Hill *et al* (1998) study that measured average percent fine sediments for different sources in the North Halawa Watershed:

- Hillslope soils: Average of 51% silt and clay
- Stream banks: Average of 12% silt and clay
- Stream bed: Average of 2% silt and clay

Table 5.1: Summary of Procedures for Calculating Yield for the Significant Erosion Processes

Process/ Reference	Application	Approach/Methodology	Annual Erosion Rate[1]	Percent Fines Adjustment	Delivery Ratio	Statement of Accuracy
Shallow Landslides						
Debris Slides/Flows Peterson *et al* 1993; Ellen *et al* 1993	Steep slopes (>20°) in Koolau and Waianae Ranges	Calculated from regional frequency and probability by slope class and average size from Ellen *et al* (1993)	Varies with annual rainfall and slope	71% including attrition, from Hill *et al* (1998)	Assumed to be 1 following previous studies	Reasonably certain; inventory over 50 years
Saprolite Landslides (Peterson *et al,* 1993)	Upper subwatersheds in Koolau Range	Approximate calculation from discussion in Peterson *et al* (1993)	~40 tons/mi^2 in upper Koolau Range	Estimated to be 25%	Assumed to be 1	Uncertain; infrequent events
Creep						
Soil or Debris Creep (Hill *et al,* 1998)	Cascade, step-pool, plane-bed and pool-riffle stream types	Adopted creep rate of 0.004 m/yr for 0.5 m soil depth. Adjusted for each type based on valley wall materials	2.5 tons per mile with colluvial banks; adjusted	25% including attrition, from Hill *et al* (1998)	100%	Uncertain
Bank Erosion						
Bank Erosion Hill *et al* (1998)	Step-pool and cascade type reaches	Erosion component of 1990-92 surveys on North Halawa, assuming no significant fines in deposits	Varies with watershed area	25% including attrition, from Hill *et al* (1998)	100%	Conservative; reasonably certain
Bank Erosion Main Tributaries (Hall et al, 1998)	Pool-riffle and plane-bed stream types	Annual rate from estimated retreat in 2008 to 2010 floods. Bank heights estimated.	Varies with watershed area	25% including attrition, from Hill *et al* (1998)	100%	Reasonably certain
Surface Erosion (Natural Hillslopes)						
Landslide scars (Ellen *et al,* 1993)	Steep slopes (>20°) in Koolau and Waianae Ranges	Numbers of slides back-calculated from yield and average volume, multiplied by average area and bare soil erosion rate from El-Swaify (1990)	150 tons/acre of slide for two years per slide	71% including attrition, from Hill *et al* (1998)	100%	Conservatively high; area reasonably certain

Process/ Reference	Application	Approach/Methodology	Annual Erosion Rate[1]	Percent Fines Adjustment	Delivery Ratio	Statement of Accuracy
Animal wallows, trails and other features	Upper Forest Conservation Areas (SW 17 and 20)	No knowledge of areas of exposed soils or erosion rate. Assumed to be ½ of landslide scar erosion	Half of scar erosion	71% including attrition, from Hill *et al* (1998)	100%, preliminary assumption	Unknown
Surface Erosion (Human-Modified Slopes)						
Residential and Commercial (USGS Mililani Storm Drain A gage)	Mililani Town, military housing and development	Average annual suspended sediment discharge at USGS Mililani Storm Drain A for 2008-10 WY	26 tons/ mi^2 of urban development	Assume 100% silt and clay	100%	Reasonably certain for mature development
Agricultural Fields (El-Swaify and Cooley, 1978; El-Swaify, 2002)	Active fields, various soils, fallow, pasture, truck crops, seed corn, pineapple	Erosion rates quoted as net soil production from small watersheds based on sediment gaging, including field roads	250 to 2,300 tons/mi^2	Assume 100% of quoted yields are silt and clay	100%, assumed from measurement procedures	Reasonably certain
Military Reservations	Only active area is in Subwatershed 8	Small area actively used. Typical surface erosion rates assigned	Total of 200 to 400 tons	Assume 100% silt and clay	100%	Uncertain
Unpaved Roads (Ziegler et al, 2000; Ziegler and Sutherland,2006).	Non-agricultural roads throughout watershed	Annual erosion estimated from rainfall excess and sediment loads, adjusted for traffic	12-16 tons per mile	Assume 100% silt and clay	Adjusted from Coe (2006)	Moderately uncertain
Paved Roads	Primarily highways and main roads between developments	Most paved roads included in residential & commercial development yields. Yields from Reid and Dunne (1984) for paved roads applied to highways and thoroughfares	3 to 4 tons per mile	Assume 100% silt and clay	100%	Uncertain

5.2.2 Soil Bulk Densities

Fine sediment yield is typically quoted as weight or weight per unit area; erosion calculated for the sediment sources is often quoted as a volume. Bulk densities for the eroded soils are required to convert volumes to weights of fine sediment in the budget. Where suitable information is available, soil bulk densities are defined from the soil database. Where it is not, they are assumed to be between 1.3 and 1.5 Mg/m^3 (81 to 94 lbs/ft^3).

5.2.3 Attrition Contributions

Hill *et al* (1998) also estimated attrition for the sediments eroded from soils in the North Halawa Valley based on abrasion-mill experiments. The attrition of sand and fine gravel sizes samples over a simulated 8 km of bed load transport ranged from 40% for the debris flow deposits, 52% for the channel bank sediments, and 36% for the bed material deposits.

Attrition was included in the sediment budget by adjusting the percent fines found in the original deposit to include the potential additional production during transport. The overall grain size distributions for the various deposits are not known but the percent fines quoted above have been roughly adjusted for attrition of the sand and gravel component, as follows:

- Hillslope soils: Average of 71% silt and clay with attrition
- Stream banks: Average of 25% silt and clay with attrition
- Stream bed: Average of 7% silt and clay with attrition

The above average percent fines are uncertain and potentially introduce significant errors into the budget calculations.

5.3 Shallow Landslides

5.3.1 Inventories and Studies

The most useful studies for estimating erosion from shallow landslides are the inventory and analysis of shallow landslide characteristics prepared by Peterson *et al* (1993) for the Honolulu District, and the analysis of landslide distribution in the debris flow hazard report prepared by Ellen *et al* (1993) from the inventory. The hazard analysis by Ellen *et al* (1993) described the probability of a debris slide/flow initiating by slope class and recommended adjustments to these probabilities to account for varying annual rainfall. These analyses provide the basis for estimating debris slide/flow yields in the Koolau Ranges (Appendix C).

5.3.2 Saprolite Landslide Yields

Saprolite landslides were included in the inventory of Peterson *et al* (1993) but they were difficult to identify and occurred only rarely. They estimated that between 3 and 8 saprolite landslides occurred in the Honolulu District over the 50 years of their inventory, or about one per decade. Saprolite landslide yields were estimated from an approximate average size, an approximate steep land area for the Honolulu District, and an estimated fine sediment percentage, and then applied to steep lands in the leeward Koolau Ranges.

5.3.3 Debris Slide/Flow Yields

The annual probabilities of initiating debris slides/flows by slope class (Ellen *et al,* 1993) were multiplied by the average landslide volume, the percent fine sediment, and the bulk density to calculate fine sediment yields by slope class. The AFSY by slope class for the upper Koolau Range was then adjusted and applied to the slope distribution of the other subwatersheds in the Koolau Range and the subwatersheds that lie in the upper Waianae Range.

5.4 Soil Creep

There do not appear to be any long-term observations of creep rates on Oahu or in the Waikele Watershed. Hill *et al* (1998) attempted short-term measurement of creep as part of their sediment budget study in North Halawa Watershed. Construction damage to some of their sites resulted in them adopting a typical rate of 0.004 m/year over a soil depth of 0.5 m for their studies which was also adopted for this study. This typical rate was from tropical studies by Lewis (1976) and Saunders and Young (1983). Appendix C provides details on the application to the Waikele Watershed.

5.5 Stream Banks

There are only two studies on Oahu that have measured stream bank erosion and only one has considered fine sediment yield. Hill et al (1998) estimated fine sediment yield from bank erosion along about 10 miles of North Halawa Stream. The North Halawa measurement reach is steep (7% average) so the results are thought to be most appropriate for the step-pool and cascade stream types in Waikele Watershed.

The other erosion study was part of the USGS program for Suspended-Sediment Monitoring for Waikele Watershed. Re-surveys of cross-sections established in 2007 for water years up to 2010 by the USGS were provided to NHC and were used to estimate annual bank erosion rates. The results are particularly useful because the re-surveys include the very large December 2008 flood.

These two sets of measurements were used to adjust a general model of annual bank erosion rate as a function of watershed area, which was then applied to calculate bank erosion by stream type for different subwatershed areas.

In general, stream bank erosion is often compensated by deposition elsewhere in the channel, roughly maintaining the typical cross sectional area. For the fine sediment yield, we have assumed that these deposits typically contain an insignificant quantity of fine sediment so that over the period of the sediment budget, the erosion will not require adjustment to predict the fine sediment yield. Such an assumption is conservative and will over-predict actual net yields where banks are formed by the stream and there is little or no net change in cross sectional area.

5.6 Sheetwash in Conservation Areas

Sheetwash erosion in conservation areas will occur where soils are exposed, primarily on landslide scars, areas exposed by feral pigs or other animals, and fire scars. For all these areas, we assume that erosion will occur at the average of the bare soil rates defined by El-Swaify (1990) of about 350 Mg/ha/year (150 tons/acre/year). This erosion rate is very high and likely provides an extremely conservative estimate of the AFSY from this source.

Little is known of the AFSY from disturbance by feral pigs. It was assumed to only occur in Subwatersheds 17 and 20 and to provide about half the yield calculated for sheetwash erosion from landslide scars. Appendix C provides details on how areas of exposed soil are calculated, fine sediment percentages, and sediment delivery ratios.

5.7 Sheetwash Erosion from Human Activities

Sheetwash erosion is accelerated on areas disturbed by human activities such as agriculture, military training, urbanization, and road construction. Of these, the yield from agricultural fields has been studied intensively; less information is available to predict sediment yields from roads and training grounds. The different sources are discussed briefly below; details are in Appendix C.

5.7.1 Agricultural Fields

Soils losses from agricultural fields on Hawaii were first measured in the 1970s (El-Swaify and Cooley, 1978). These measurements have been extended to other crops in later publications by El-Swaify (2000, 2002). The value of the original measurements is that water and sediment discharges were measured at the outlet of small agricultural watersheds with areas from 2 to 7 acres over several years for harvest cycles of pineapple and sugar cane crops. Consequently, the measured yields are net of erosion and deposition in the fields, include yield from plantation roads, and are representative of the contribution to streams. Appendix C provides details on the adopted crop yields and the sources of the information.

5.7.2 Native-Surfaced and Paved Roads

Studies of erosion from native-surfaced roads are common in the tropics and studies on Oahu include those by Ziegler et al (2000) and Ziegler and Sutherland (2006). Specific observations of erosion reported in these two studies were extrapolated to average annual yield with annual rainfall and estimates of runoff volumes and then adjusted for a typical sediment delivery ratio. Details are included in Appendix C.

Paved roads in the Waikele Watershed primarily occur in residential and commercial areas and their contribution to the sediment budget is assumed to be included in the urban area AFSY discussed in the next subsection. We have assumed some AFSY from highways and major thoroughfares within the watershed. Details are included in Appendix C.

5.7.3 Urban Areas

The USGS measured sediment discharge from the Mililani Storm Drain A from WY 2008 to 2010. The average suspended sediment load was assumed to be representative of the AFSY from mature residential and commercial development in the Waikele Watershed. We have further assumed that sediment yields from construction have been managed by various regulatory agencies and that the AFSY to streams from this source is zero.

5.7.4 Military Reservations and Training Areas

Active training areas on military reservations include only a small portion of Subwatershed 8 and only a small portion of that area appears to be used. AFSY was calculated from typical yields under disturbance for this area, as described in Appendix C.

6. SEDIMENT BUDGETS

6.1 Introduction

This chapter provides the results of calculating fine sediment yield from the significant erosion processes for Subwatershed 17 (Upper Kipapa), for the five tributary watersheds, and for the overall Waikele Watershed to the Waikele Stream near Waipahu gage. Results are provided in the two following sections.

The total fine sediment yield calculated from the erosion processes is compared to the measured AFSY at the Kipapa Stream near Wahiawa and Waikele Stream at Waipahu gages (see Table 3.4). As briefly discussed in Section 3.9, the adopted AFSY at the gages is the average over the years from 1973 to 2010.

6.2 Upper Kipapa Fine Sediment Budget

Table 6.1 summarizes the fine sediment erosion calculations for Subwatershed 17 and the measured AFSY at the Kipapa near Wahiawa gage.

Table 6.1: Sediment Budget for Upper Kipapa Subwatershed

Erosion Process	AFSY (tons)	Comment
Debris Slides/Flows	2,100	Reasonably certain
Saprolite Landslides	170	Uncertain
Soil Creep	30	Likely reasonable
Stream banks	450	Conservative
Landslide Scars	330	Conservative
Feral Pigs and Goats	170	Uncertain
TOTAL EROSION	3,250	
MEASURED AFSY AT GAGE (1973-2010)	3,700	

The AFSY predicted from the sum of the erosion processes came to about 88% of the AFSY measured at the stream gage. Given the uncertainty in the AFSY at the gage – most of the daily loads were estimated from a discharge-sediment load relationship – and the uncertainty in the calculations for the erosion processes, it was assumed that the erosion estimates for upland areas in the Koolau Range were reasonably satisfactory and required no adjustment. Reduction of the uncertainties in the erosion estimates in Table 6.1 would require considerable further investigation and analyses.

6.3 Major Tributaries Fine Sediment Budgets

Table 6.2 summarizes the results of the fine sediment erosion calculations for each of the five major tributaries. The erosion processes have been divided into natural hillslope erosion, human modified hillslope erosion, and stream erosion.

The rightmost column of Table 6.2 provides the overall budget for the Waikele Watershed by summing the results for the tributary watersheds. Total yields calculated from erosion for each tributary watershed are provided at the bottom of the table. There are no gages at the outlet of the tributary watersheds so they are unconfirmed.

Table 6.2: Sediment Budget Summary for the Tributary Watersheds

Erosion Process	AFSY (tons) by Tributary Watershed [1]					Waikele Watershed
	1	2	3	4	5	
Natural Hillslope Processes						
Debris Slides/Flows	1,400	2,600	220	170	0	4,400
Saprolite Landslides	80	170	0	0	0	250
Soil Creep	20	80	20	40	10	170
Landslide Scars	240	420	40	20	0	730
Feral Animals	110	170	0	0	0	280
Subtotal						*5,800*
Human-Modified Hillslope Processes						
Urban Areas	40	90	60	10	50	250
Military Training	0	0	300	0	0	300
Agriculture	20	2,300	2,900	6,500	4,700	16,400
Unpaved Roads	170	530	560	340	520	2,100
Paved Roads	0	50	50	0	0	100
Subtotal						*19,200*
Stream Bank Erosion						
All Stream Types	560	1,960	750	820	1,010	*5,100*
TOTALS	*2,600*	*8,400*	*4,900*	*7,900*	*6,300*	*30,100*
MEASURED AFSY AT WAIKELE GAGE (1973 to 2010)						26,800

1. Tributary watershed 1 is Waikakalaua; 2 is Kipapa; 3 is Upper Waikele; 4 is the Waianae Range; and 5 is lower Waikele.

6.4 Waikele Watershed Fine Sediment Budget

The total annual fine sediment erosion calculated for the Waikele Watershed was 30,100 tons. The calculated erosion was a few percent greater than the AFSY measured at the Waikele Stream at Waipahu gage (Table 6.2). Given the close agreement between the erosion estimates and the measured, no adjustments were proposed to the erosion calculations. However, comparing Tables 6.1 and 6.2 suggests that the contribution of natural processes to the erosion from total watershed may be slightly underestimated and human-caused ones may then be slightly over-estimated.

Table 6.2 shows that the dominant source of fine sediments in the Waikele Watershed is surface erosion from human-modified terrain, and that most of these sediments are derived from erosion in agricultural fields. The human-modified terrain provides about 64% of the annual fine sediment yield; natural hillslope process provide about 19%; and stream bank erosion throughout the watershed provides the remaining 17%.

The individual dominant erosion processes are surface erosion from agriculture, debris slides and flows, unpaved roads, and stream bank erosion. These four processes contribute over 90% of the annual fine sediment yield. The other seven erosion processes provide the remaining annual fine sediment yield and are relatively insignificant contributors in the Waikele Watershed.

The total erosion and the contribution of the different erosion processes vary significantly from one tributary watershed to the next. Kipapa and the Waianae Tributary watersheds provide the greatest erosion; Waikakalaua tributary watershed the least. In Kipapa watershed, natural and human-modified slope processes contribute about the same amount to the total. In Waianae watershed, agriculture provides the vast bulk of the eroded fine sediment.

7. CONCLUSIONS & RECOMMENDATIONS

This report developed a rapid sediment budget for the Waikele Watershed, primarily from existing studies or other information in the watershed or on the island of Oahu. The budget was limited to predicting average annual fine sediment yield, where fine sediment consisted of silt and clay (grain sizes less than 62.5 microns) and the yields were averages over a thirty to forty year period.

The budget process consisted of identifying the significant erosion sources, developing procedures to estimate their average yield, and comparing the total yield predicted from the erosion sources to yields measured at the USGS gage at the outlet of the watershed and in the upper Kipapa subwatershed. Deposition was assumed to be zero, which was a reasonable assumption for the silt and clay, which is carried as wash load in the streams in the Waikele Watershed, and because there are no significant lakes, reservoirs, or other sediment traps. Some deposition will occur on the floodplain and at some sites within the stream, but these are thought to be minor compared to the overall erosion.

The significant erosion sources were debris slides/flows, saprolite landslides, soil creep, stream bank erosion, sheetwash erosion from exposed soils on natural hillsides, and sheetwash erosion from exposed soils on human-modified hillslopes. The most-studied of the erosion processes – debris slides/flow, stream bank erosion, surface erosion from agricultural fields, and surface erosion from unpaved roads – also turned out to be the most significant ones to total erosion budgets. Consequently, the least certain estimates are from the relatively minor contributions to the budget and the most certain ones are from the most significant contributing processes.

The erosion estimates were roughly confirmed by comparing the total predicted erosion to the long-term fine sediment yield measured at the gaging stations. In the case of the upper Kipapa Watershed, the erosion estimates produced a little less sediment than had been measured at the gage by the USGS. For the Waikele Watershed (above Waipahu), the erosion computations produced slightly more sediment than had been measured at the gage. This does not confirm that the erosion estimates are accurate. First, there are considerable uncertainties in the fine sediment yield at the gages. This occurs because large parts of the record of daily loads were filled with a daily flow-daily load relationship, and because fine sediment as a portion of total suspended load was estimated from the results of a study by Hill et al (1988). Second, compensating errors in the yield estimated from different erosion processes could match the yield at the gage even though the individual estimates were not very accurate.

One of the purposes of preparing the sediment budget was to answer specific questions about the relative contribution of different erosion sources and their distribution within the watershed. The first issue to be addressed is the relative contribution of streams and the land surface to the total erosion. Stream bank erosion was estimated to provide about 17% of the overall fine sediment yield from the Waikele Watershed. The percentage of the total varied from tributary watershed to tributary watershed but not by a great amount; the range of percentages was from 10 to 23%. The greatest contribution was from the Kipapa tributary watershed.

As discussed in Chapter 5, the yield from stream bank erosion is assumed to be conservative. First, it was assumed that deposition that occurred to maintain channel dimensions had insignificant quantities of fine sediment. This may be true over some time periods but is unlikely to be correct over the long term. Also, the equations used to adjust the measured erosion rates to subwatersheds in the upper watershed was not adjusted to account for less erodible deposits and more exposed bedrock.

For the overall Waikele Watershed, the most significant contributions to total fine sediment erosion were from agriculture (54%), debris slides/flows (15%), stream banks (17%) and unpaved roads (7%). These four erosion sources contributed over 90% of the fine sediment delivered from Waikele Watershed. The fine sediment delivered from human-modified areas – agricultural fields, urban development, military training areas, unpaved and paved roads – was about 64% of the overall fine sediment yield.

Over the period of the budget, the area devoted to agriculture and the particular crops grown on the fields have varied as sugarcane and pineapple production have declined, while that of truck crops and seed corn has increased. The general trend has been for a smaller total area devoted to agriculture, as it is replaced by urban development, but for greater sediment production per unit area from the more recent crops. This has resulted in an increase in the fine sediment yield from agriculture since the 1980s despite the loss of about one-third of the agricultural land.

A second important purpose of the sediment budget was to help recalibrate or revise the sediment routines in the watershed model (WARMF or HSPF) so that the simulated sediment loads better match the results of the budget with respect to stream- and land surface-based erosion sources.

Application to WARMF and HSPF Routines for Land-Based Erosion

The land-based erosion components of the WARMF and HSPF models are similar, both being based on rainfall and turbulent detachment of particles from the surface and the transport of fine sediment in suspension. Calibration of the governing equations to specific parts of the watershed will require manipulation of the model parameters to match the yields from specific cover, slope, and/or soil combinations. Landslides might best be treated as soil erosion occurring over a range of steep slopes in the subwatershed with rates calibrated to those in

Appendix Tables C1 to C3. The key parameters affecting these processes in the WARMF model are soil erosivity factors, the rainfall or flow detachment factors, and the cropping factor. HSPF utilizes coefficients in soil detachment and washoff equations for pervious surfaces and accumulation and washoff rates for impervious surfaces.

Both WARMF and HSPF also require the user to define the fractions of sand, silt, and clay present in the runoff from the land surface. It is common to define these fractions using data of the source material defined by the NRCS in their SSURGO database. For the Waikele basin, the NRCS reports 18% sand and 82% silt and clay for the upper slopes of the Koolau Range and a slightly higher silt and clay fraction of approximately 95% for the Waianae Range and the silty-clay soil series that dominate the valley between the two ranges. In Section 3.8 we adjusted observed total in-stream suspended sediment loads or yields to fine sediment loads or yields by applying a multiplier of 86% based on silt and clay fractions reported by Hill *et al* (1998) for North Halawa stream, a number similar to the silt and clay fraction reported for the Koolau Range soils by the NRCS. The sand, silt, and clay fractions defined in the WARMF or HSPF watershed models should reflect an appropriate combination of these data sources. If fractions are defined based on source materials alone, they should also be adjusted to account for the higher likelihood that sand particles will be deposited in the overland flow plain before reaching the stream than finer sand and silt.

Application to WARMF and HSPF Routines for Stream Erosion

The stream-based erosion routine in the WARMF model addresses both bed and bank erosion. The bed erosion routine calculates an erosion rate from the bed based on the difference between the observed velocity and the critical velocity for movement of the bed materials. Given that this process is thought to be a minor component of the overall fine sediment yield, it may be advisable to assign particle diameters to the various reaches so that the critical velocities are not exceeded, essentially eliminating erosion from this source.

Bank erosion is calculated in the WARMF model as the cube of the local velocity multiplied by the sum of parameters that represent the effect of vegetation and bank stability on potential erosion rates. The fine sediment yield, as a portion of the suspended yield, is calculated from the percentage of the bank and bed material in the silt and clay size classes. This subroutine will then predict some bank erosion for all velocities that are greater than zero. In the long-run, it would be helpful to introduce a critical velocity for erosion in order to limit the periods when bank erosion occurs to flood or high flows. However, this would require modification of the WARMF model by its owners and may not occur soon.

The stream based erosion calculations in HSPF are handled by the sediment transport (SEDTRN) routines for each routing reach. Like WARMF, the module simulates the transport, deposition, and scour of fine sediment in each stream. However, HSPF does not treat bank erosion independently from that of the bed. HSPF routines for scour and deposition have unique parameter sets for non-cohesive sands (sub-routine SANDLD) vs. that used for cohesive silts and clays (sub-routine BDEXCH). Multiple sand transport algorithms are available for use by the model, and all use average stream velocity as the primary variable determining deposition or scour. Routines for silts and clays calculate deposition and scour based on critical shear stresses provided for deposition and scour.

The most practical approach for calibration of either WARMF or HSPF stream erosion routines, given deficiencies in their instream erosion routines, is to calibrate the yield from each reach in the model to the predicted fine sediment yield equations provided in Appendix C. Such an approach would require predicting the durations of velocities over a typical period and estimating suitable parameters for bank and/or reach stability to match the long-term yield.

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APPENDIX A

APPENDIX A: SUBWATERSHED PHYSICAL AND LAND USE CHARACTERISTICS

A1. Subwatershed Characteristics

As described in Chapter 2, the various subwatersheds were combined into five tributary watersheds. Table A.1 provides a summary of the watershed areas and stream lengths for the tributary watersheds.

Table A.1: Summary of Tributary Watershed Characteristics			
Watershed No.	**Stream Name**	**Area (square miles)**	**Stream Length (miles)**
1	Waikakalaua	5.8	21.0
2	Kipapa	15.5	52.3
3 and 5	Upper and Lower Waikele	16.5	31.6
4	Waianae Ranges (Ekahanui, Huliwai, Poliwai and Manuwaiahu Gulches)	8.4	26.2
	Grand Total	46.2	131.1

A2. Stream Types

Figure A.1 (from Montgomery and Buffington, 1997) shows a typical stream longitudinal profile and the succession of stream types that are commonly observed.

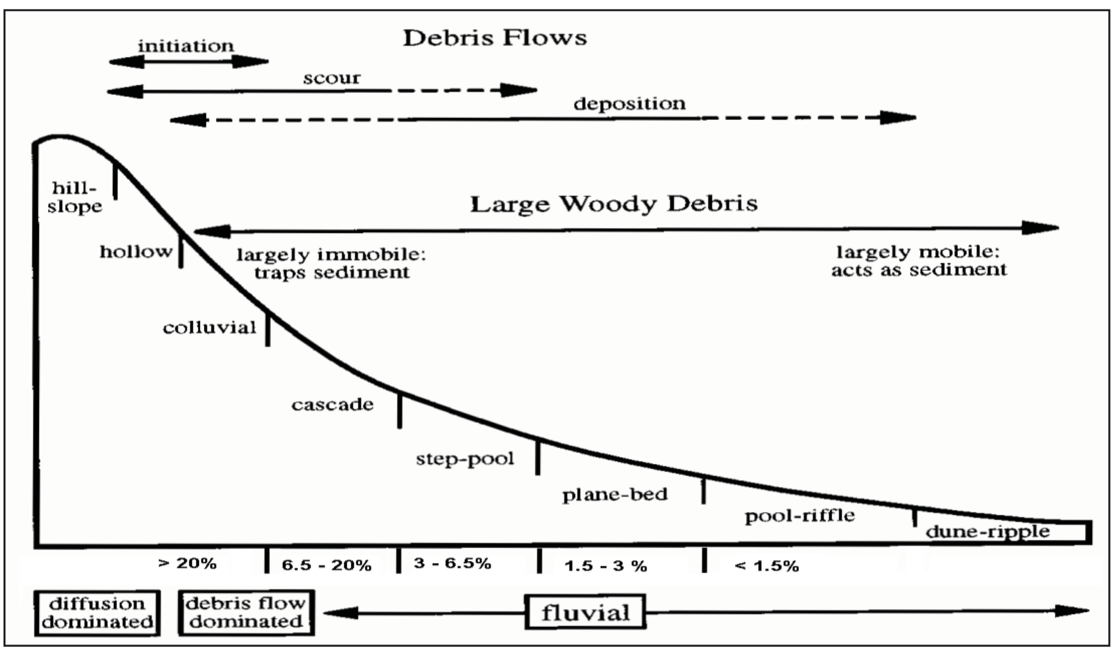


Figure A.1: Idealized long profile showing stream types (modified from Montgomery Buffington, 1997)

Table A.2 summarizes the length of each stream type observed for the 20 subwatersheds shown on Figure 2.1. Stream types were assigned based on average slopes calculated over stream segments that were at least 1,500 feet long.

Table A.2: Length of Stream by Type Length for each Subwatershed						
Subwatershed No	Stream Name	Channel Length by Stream Type Class (miles)				
		Pool-riffle	Plane-bed	Step-pool	Cascade	Colluvial
1	Waikele	2.8	0.6	0.3	-	0.1
2	Waikele	0.5	1.3	0.3	-	-
3	Waikele	1.7	2.2	0.3	0.5	-
4	Waikele	1.0	-	-	-	-
5	Waikele	1.4	1.2	0.3	-	-
7	Waikele	3.9	0.3	-	-	-
8	Waikele	0.4	2.9	3.2	4.6	1.8
Sub-Total Waikele Stream		**11.7**	**8.4**	**4.4**	**5.2**	**1.9**
9	Ekahanui-Huliwai Gulch	0.3	3.5	4.8	4.4	0.6
10	Poliwai-Manuwaiahu Gulch	1.2	6.2	2.2	1.8	1.2
Sub-Total Poliwai-Ekahanui-Huliwai		**1.6**	**9.7**	**7.0**	**6.2**	**1.8**
11	Kipapa	2.9	2.1	0.7	0.3	-
12	Kipapa	-	0.3	0.3	0.3	-
13	Kipapa	-	0.3	0.6	0.3	-
14	Kipapa	0	0	0.9	0.4	-
15	Kipapa	3.3	3.2	1.8	0.3	-
16	Kipapa	0.9	3.6	6.0	1.7	0.3
17	Kipapa	2.2	5.8	5.7	6.8	1.0
Sub-Total Kipapa		**9.3**	**15.3**	**16.3**	**10.2**	**1.3**
18	Waikakalaua	6.2	1.4	0.9	-	-
19	Waikakalaua	1.8	1.4	-	-	-
20	Waikakalaua	1.4	4.0	2.4	0.8	0.6
Sub-Total Waikakalaua		**9.4**	**6.9**	**3.3**	**0.8**	**0.6**
Grand Total		**32.0**	**40.3**	**31.0**	**22.3**	**5.5**

A3. Stream Profiles

Upper and Lower Waikele Stream

Upper Waikele Stream extends upstream of the confluence with Waikakalaua Stream, past Wheeler and Schofield military bases and into the Waianae Mountains. This nine-mile long section of the stream is ephemeral (Photos A.1 and A.2); the lower eight miles below

Waikakalaua Stream are perennial, gaining flow from Koolau tributaries on the east side of the basin. The Waikele Stream long profile (Figure A.2) begins with a steep, cascade type reach in the Waianae Mountains that changes quickly to a plane-bed type at river mile 16, and then to a pool-riffle channel before river mile 14. The stream channel then steepens into a plane-bed type for a short 3-mile stretch upstream of the confluence with Kipapa Stream (Photo A.3), before flattening as it flows over alluvial sediments on its approach to Pearl Harbor (Photo A.4).

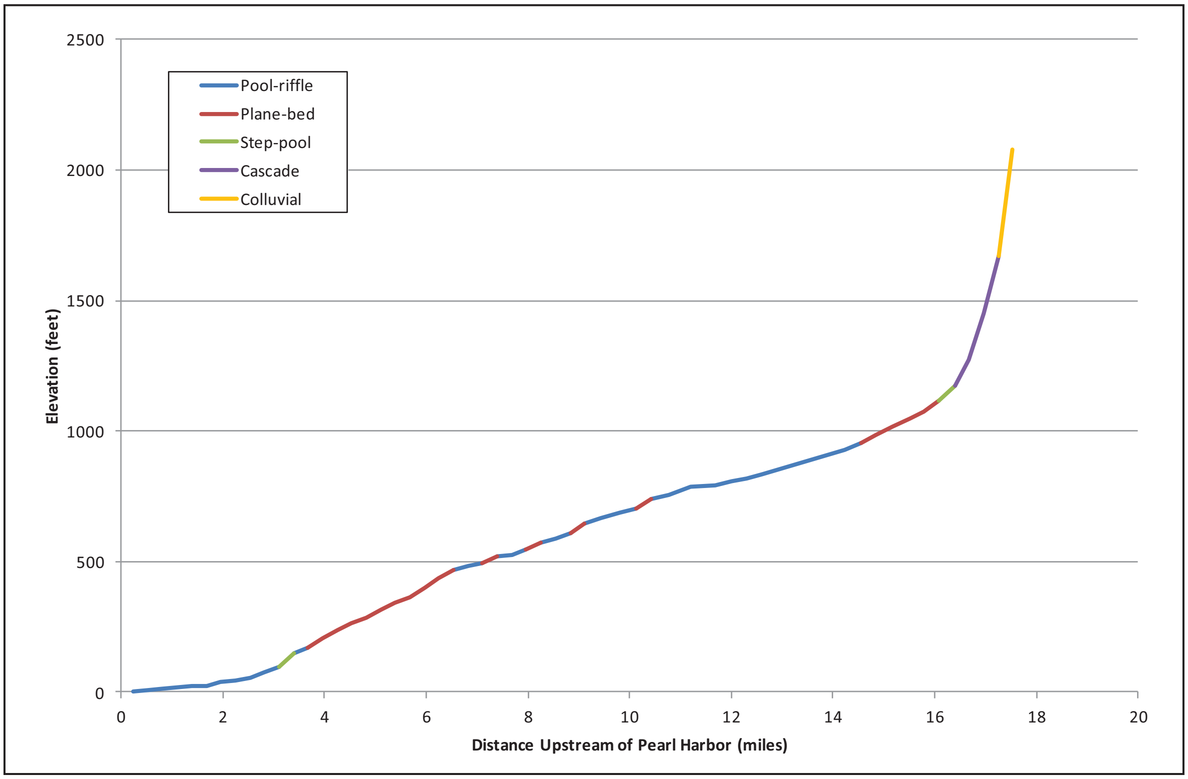


Figure A.2: Waikele Stream Long Profile

Photos A.1 and A.2: Waikele Stream near Wheeler gage site (left) and above Waikaklaua confluence (right, both taken August 2, 2011)

Photos A.3 and A.4: Waikele Stream downstream of Huliwai confluence (left, taken August 2, 2011) and looking upstream at Waipahu Street (right, taken August 3, 2011)

Kipapa Stream

Kipapa Stream is the largest tributary to Waikele Stream. Like Waikele Stream, the Kipapa long profile (Figure A.3) begins with a steep cascade type reach but it has a greater length of step-pool than Waikele (2.1 vs. 0.6 miles) in the Koolau Range before flattening and maintaining a sequence of plane-bed and pool-riffle types for the 11 miles above the confluence with Waikele Stream (Photos A.5 and A.6).

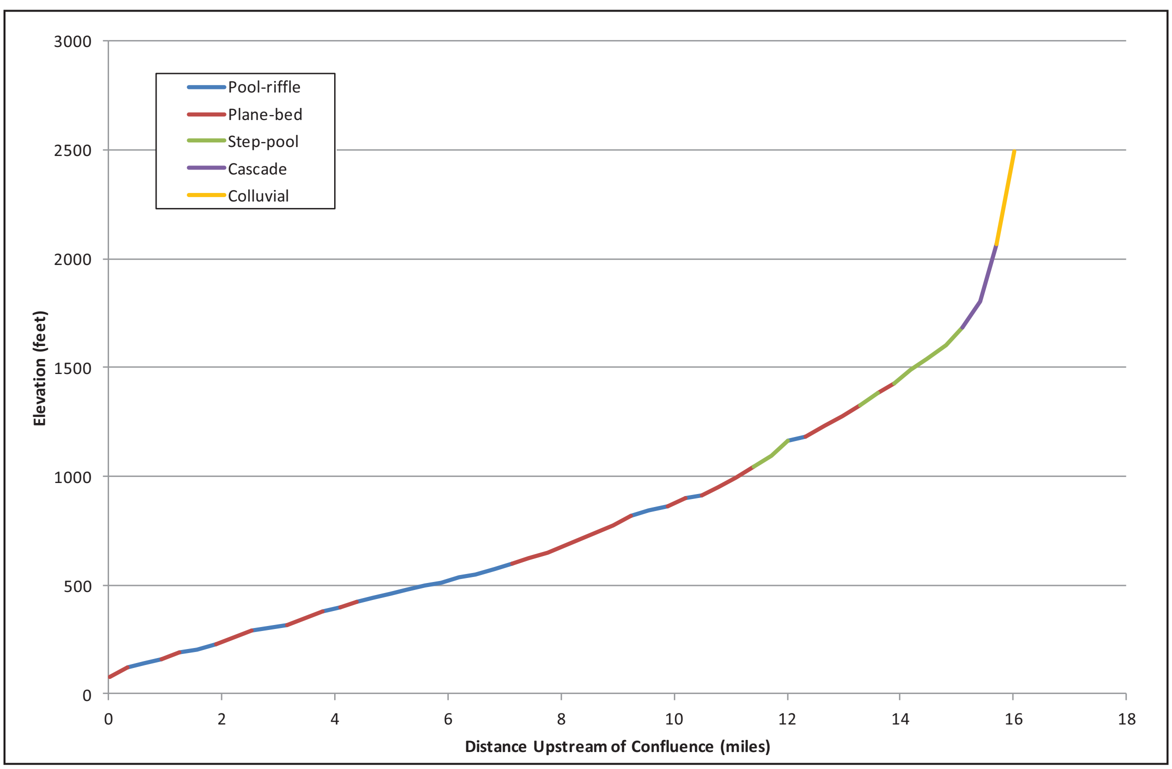


Figure A.3: Kipapa Stream Long Profile


Photos A.5 and A.6: Kipapa Stream upstream of USGS gage station (left, August 1, 2011) and looking upstream from bridge crossing upstream of Waikele Stream confluence (right, August 2, 2011)

Waikakalaua Stream

The Waikakalaua profile (Figure A.4) begins with a series of cascade and step-pool types before becoming a predominantly plane-bed type by river mile 12 and then a pool-riffle type below river mile 8. The floodplain along the lower three miles is developed and the stream is constrained by urbanization, unlike Kipapa Stream (Photos A.7 and A.8). The stream joins Waikele Stream after passing through Wheeler Air Force Base.

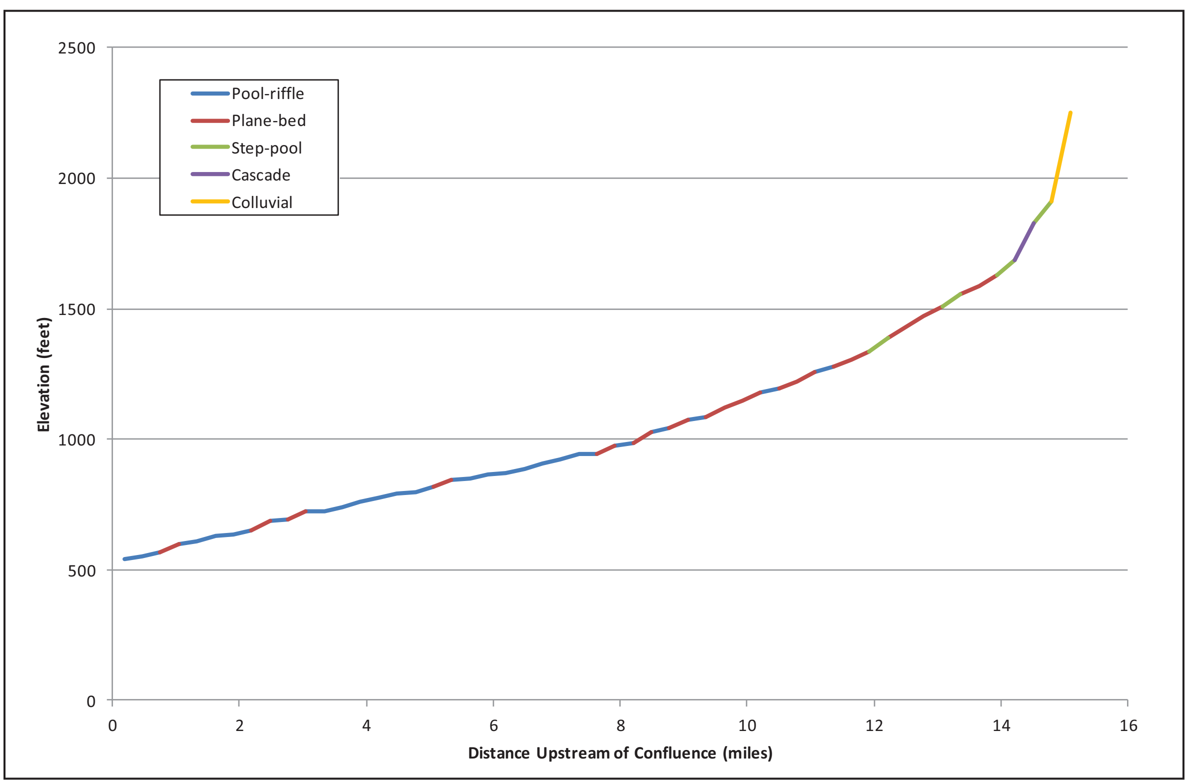


Figure A.4: Waikakalaua Stream Long Profile

Photos A.7 and A.8: Waikakalaua Stream near Wikao Street north of the H-2 Highway (left) and Waikalani Drive south of the H-2 Highway (right)

Ekahanui, Huliwai, Poliwai and Manuwaiahu Gulches

The eastern edge of the Waikele Watershed area, in the vicinity of Kunia Town, is drained by Ekahanui, Huliwai, Poliwai, and Manuwaiahu Gulches (from south to north). Like the upper Waikele Stream, these gulches are ephemeral. The profiles of Huliwai and Poliwai Gulches (Figures A.5 and A.6) show mostly steeper channel types and very little pool-riffle type.

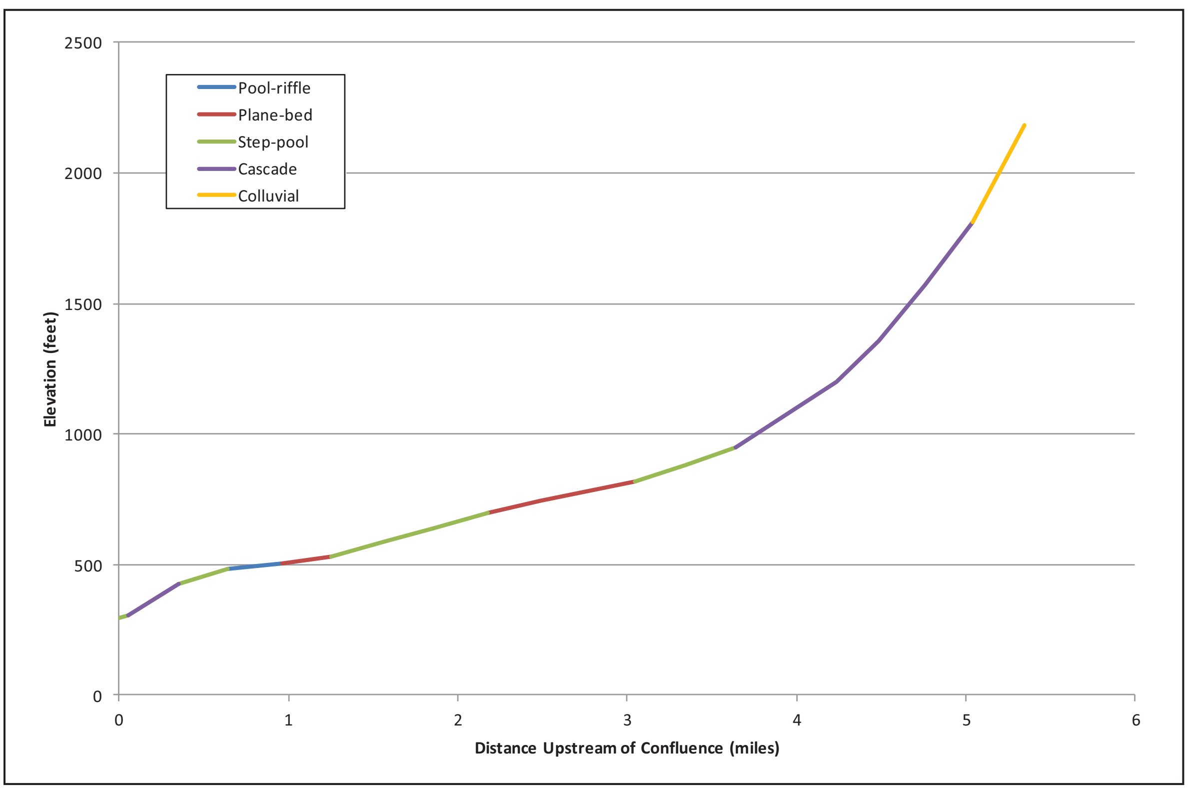


Figure A.5: Huliwai Gulch Long Profile

Huliwai Gulch has a steep segment at its downstream end where it drops from the Oahu Plain into the gulch eroded by Waikele Stream. Manuwaiahu Gulch, which does not include any stream segments steeper than plane-bed, has a different long profile than the other three gulches.

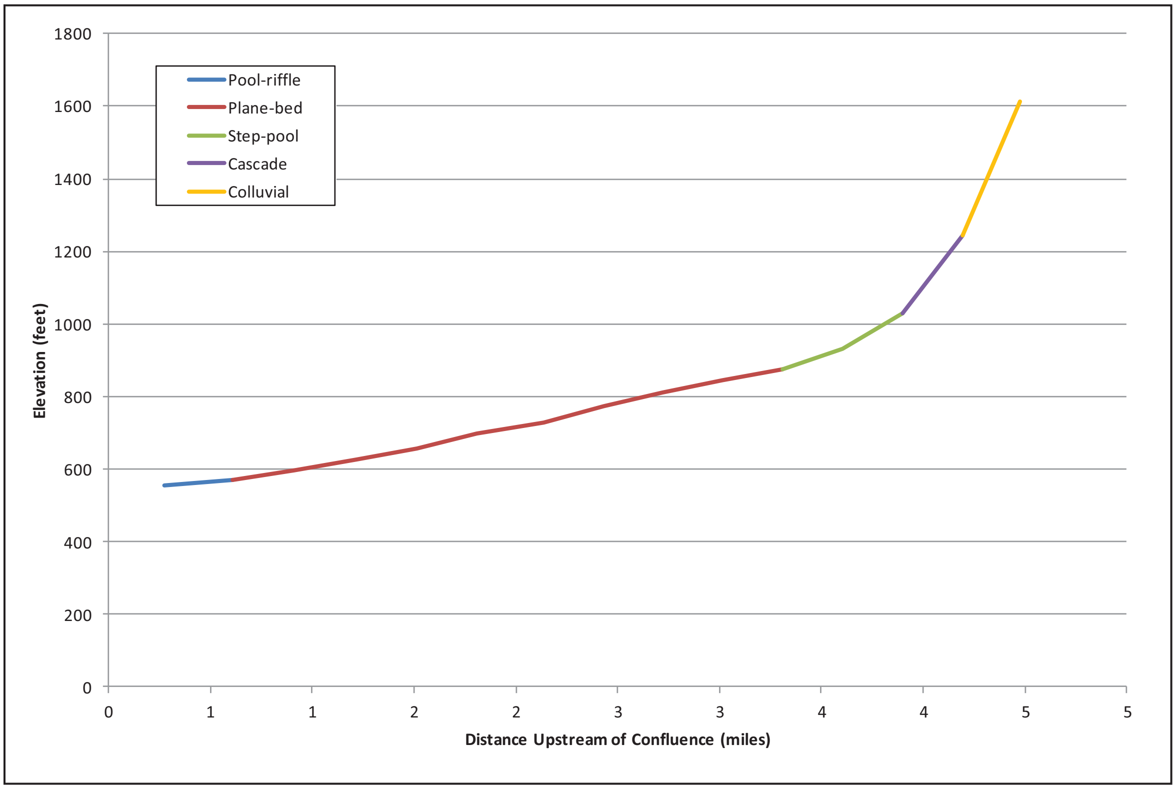


Figure A.6: Poliwai Gulch Long Profile

A5. Land Surface Slopes

Land surface slopes were calculated from the cells in the 10-meter DEM. Table A.3 (following page) divides the area of each subwatershed into ten slope classes ranging 0 to 5% to 80% to 250%; the slope class with the greatest portion of the subwatershed area is highlighted. Over half of the area in the Waikele Watershed (60%) falls into the three classes that have slopes less than 20%. The areas with low slopes mostly lie within the Oahu Plain; the steeper slopes are in the Koolau and Waianae Ranges.

The three subwatersheds with the greatest average slopes – 16, 17, and 20 – are all located along the crest of Koolau Range and have over half their area with slopes over 40%. The subwatersheds in the Waianae Mountains – 8, 9, and 10 – have far less of their total area made up by these steep slopes. The areas in the steepest slope classes were used in the calculation of sediment yields from landsliding (Appendix C).

Table A.3: Percentage of Subwatershed Area by Slope Class, based on 10-meter DEM											
Sub-Basin Group	Receiving Body	Percentage of Area by Slope Class								Average Slope (%)	Average Elev. (ft)
		0 - 5%	5 - 10%	10 - 20%	20 - 30%	30 - 40%	40-60%	60-80%	80 - 250%		
1	Waikele Str.	58%	26%	9%	3%	1%	2%	1%	0%	7.9	360
2	Waikele Str.	55%	12%	11%	5%	4%	6%	4%	3%	15.3	460
3	Waikele Str.	56%	12%	10%	6%	4%	7%	3%	1%	13.1	640
4	Waikele Str.	86%	13%	1%	0%	0%	0%	0%	0%	3.1	690
5	Waikele Str.	67%	12%	9%	5%	4%	3%	0%	0%	7.6	760
6	Waikele Str.	93%	6%	1%	0%	0%	0%	0%	0%	2.4	850
7	Waikele Str.	68%	13%	10%	5%	2%	1%	0%	0%	6.7	880
8	Waikele Str.	7%	11%	22%	16%	11%	15%	11%	7%	33.9	1460
9	Ekahanui-Huliwai Gulch	18%	22%	18%	9%	7%	12%	9%	5%	26.0	1150
10	Poliwai Gulch	34%	23%	16%	8%	6%	9%	4%	1%	16.3	980
11	Kipapa Str.	42%	17%	13%	7%	5%	8%	5%	2%	17.0	470
12	Kipapa Str.	86%	12%	2%	0%	0%	0%	0%	0%	3.1	590
13	Kipapa Str.	57%	24%	11%	3%	2%	2%	1%	0%	7.8	580
14	Kipapa Str.	57%	25%	11%	3%	2%	2%	0%	0%	7.5	830
15	Kipapa Str.	7%	11%	16%	13%	13%	24%	13%	3%	34.8	840
16	Kipapa Str.	1%	3%	8%	11%	15%	34%	22%	7%	47.4	1280
17	Kipapa Str. (Upper)	1%	2%	5%	8%	10%	28%	28%	19%	57.2	1560
18	Waikakalaua Str.	34%	12%	13%	10%	10%	16%	6%	1%	21.3	850
19	Waikakalaua Str.	54%	25%	12%	4%	3%	3%	0%	0%	7.9	720
20	Waikakalaua Str. (Upper)	1%	2%	5%	8%	11%	31%	29%	14%	55.3	1620
All Study Area		33%	14%	12%	8%	7%	13%	9%	4%		

[1] Cells marked in red identify the slope class with the largest area in each sub-basin group.

A5. Soils

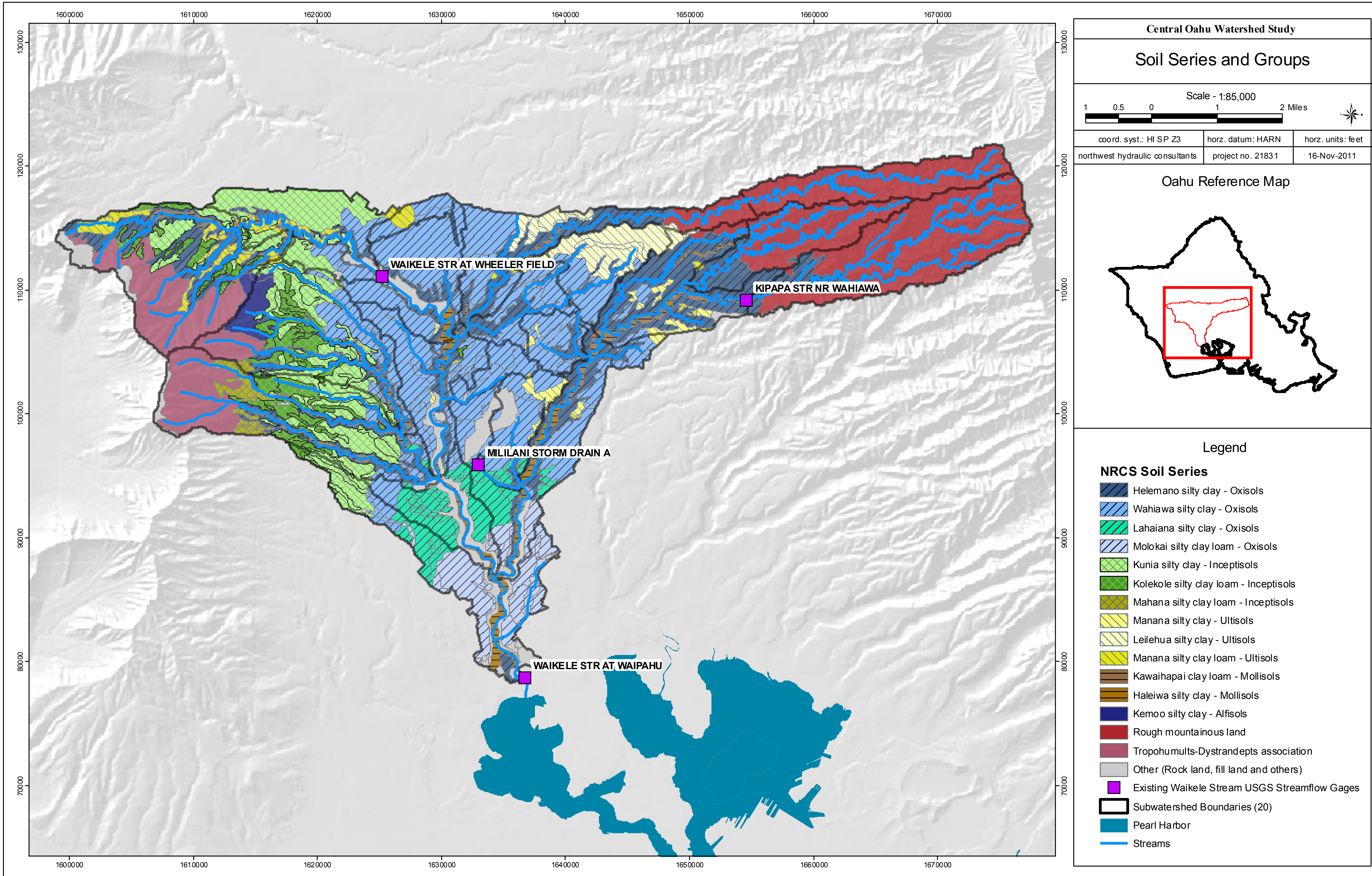
There are dozens of NRCS soil types within the Waikele Watershed. The 17 soil types with the greatest area in the watershed are listed in Table A.4 (following page) and shown on Figure A.7. Parameters for each soil in the study area were obtained from the Soil Survey Geographic database (SSURGO), which is GIS-based polygon coverage of soil classifications (NRCS, 2008). The database includes the soil property values narrated in regional NRCS soil reports. The K factor is an indication of potential soil erodibility based on soil structure.

Table A.4: NRCS Soil Series within Waikele Watershed

NRCS SSURGO Soil Database			Measured Erosion Potential by Soil Group (Mg/ha/yr)[2]	% of Study Area
Soil Series	Soil Group – Order	K Factor		
Helemano silty clay (30 to 90 percent)	Tropeptic Haplustox - Oxisols	0.17		18.1
Wahiawa silty clay (0 to 15 percent)	Tropeptic Eutrustox - Oxisols	0.15	42	21.4
Lahaina silty clay (0 to 15 percent)	Typic Torrox – Oxisols	0.17	57	3.7
Molokai silty clay loam (0 to 25 percent)	Typic Torrox – Oxisols	0.2		3.6
Kunia silty clay (0 to 15 percent)	Ustoxic Humitropepts – Inceptisols	0.17		9.4
Kolekole silty clay loam (1 to 25 percent)	Ustoxic Humitropepts – Inceptisols	0.17		3.9
Mahana silty clay loam (6 to 35 percent)	Oxic Dystrandepts - Inceptisols	0.43	117	0.8
Manana silty clay (3 to 25 percent)	Orthoxic Tropohumults - Ultisols	0.10	29	0.9
Leilehua silty clay (2 to 12 percent)	Humoxic Tropohumults - Ultisols	0.10		2.8
Manana silty clay loam (6 to 35 percent)	Orthoxic Tropohumults - Ultisols	0.10		1.6
Kawaihapai clay loam (0 to 15 percent)	Cumulic Haplustolls - Mollisols	0.17		1.9
Haleiwa silty clay (0 to 6 percent)	Typic Haplustolls - Mollisols	0.17		1.9
Kemoo silty clay (12 to 35 percent)	Oxic Rhodustalfs - Alfisols	0.17		0.9
Other soils[1]	Varies	varies		0.9
Rough mountainous land	N/A	0.20		16.8
Tropohumults-Dystrandepts association	N/A	0.10		7.0
Rock Land	N/A	0.10		2.4
Fill land	N/A	0.10		1.9
All Soils Total				100

[1] 'Other soils' are comprised of small areas of the following: Waipahu silty clay, Tropaquepts, Paaloa silty clay, Water > 40 acres, Honouliuli clay, Keaau clay, and Coral outcrop

[2] From Table 3.1 of El-Swaify (2000) 'Erosion Potential for Different Locations in Hawaii'



Central Oahu Watershed Study
Soil Series and Groups
Scale - 1:85,000
1 0.5 0 1 2 Miles
coord. syst.: HI SP Z3
horz. datum: HARN
horz. units: feet
northwest hydraulic consultants
project no. 21831
16-Nov-2011
Oahu Reference Map
Legend
NRCS Soil Series
Helemano silty clay - Oxisols
Wahiawa silty clay - Oxisols
Lahaiana silty clay - Oxisols
Molokai silty clay loam - Oxisols
Kunia silty clay - Inceptisols
Kolekole silty clay loam - Inceptisols
Mahana silty clay loam - Inceptisols
Manana silty clay - Ultisols
Leilehua silty clay - Ultisols
Manana silty clay loam - Ultisols
Kawaihapai clay loam - Mollisols
Haleiwa silty clay - Mollisols
Kemoo silty clay - Alfisols
Rough mountainous land
Tropohumults-Dystrandepts association
Other (Rock land, fill land and others)
Existing Waikele Stream USGS Streamflow Gages
Subwatershed Boundaries (20)
Pearl Harbor
Streams
WAIKELE STR AT WHEELER FIELD
KIPAPA STR NR WAHIAWA
MILILANI STORM DRAIN A
WAIKELE STR AT WAIPAHU
1600000
1610000
1620000
1630000
1640000
1650000
1660000
1670000
130000
120000
110000
100000
90000
80000
70000

Figure A.7

The measured erosion potential column presents some soil loss rates in Hawaii that quantify soil erosion, assuming there was no cover or attenuation of sediment (El-Swaify, 2000).

Most of the central plain is comprised of Wahiawa, Helemano, Kunia, or other silty clay soil series while the Koolau and Waianae Ranges are classified as "rough mountainous land" and "Tropohumults-Dystrandepts association", respectively. There are no descriptions for the mountainous land; the topohumults-dystrandepts are reported as having relatively low erodibility, expressed as K in RUSLE by El-Swaify (2000).

A6. Land Use/Land Cover

The land use classification in Table A.5 is based on previous work completed by the Department of Health (DOH) in coordination with NHC. Like the classification used in PB Americas and NHC (2010), the base data are the 2005 C-CAP land cover, but the DOH land use classifications also include manual delineations of urban land uses and agricultural crops. A report describing the DOH classification effort has not been published.

In summary, DOH manually converted the C-CAP "Impervious surface" and "Open Space Developed" categories to "impervious surface travelled", "impervious surface non-travelled", "urban grass", and "golf course" categories. The golf course category included both "open spaced developed" and "scrub/shrub" C-CAP categories. Agricultural areas (C-CAP cultivated lands and grassland categories) were divided into five crop types and a sixth category was added for roads and other compacted areas within the fields.

The largest four land covers within the 46.2 square mile study area included forest (21.3 square miles), agricultural lands (9.1 square miles), and urban or developed areas (9.0 square miles); these and other land covers are presented in Figure 2.3 and tabulated in Table A.5. Forested land dominates the slopes of the Koolau and Waianae Ranges which are designated and managed as conservation areas. Most of the developed impervious land use is located in the central valley portion of the study area in urban areas such as Mililani Town, Wahiawa, and both the Schofield Barracks and Wheeler AAF military bases. Agriculturally dominated subwatersheds are predominantly located on the western edge of the study area near the gulches and Waikele Stream. Kipapa Stream has relatively little agriculture in its drainage area.

Table A.5 provides the dominant land covers by subwatershed and the total area of each land cover category for the Waikele Watershed for 2005. The following section of this Appendix and Chapter 2 of the main report discuss some of the changes in land use over the past thirty years, or over about the period of suspended sediment discharge records in the Waikele Watershed (refer to Chapter 3 of the main report for details).

Table A.5: Dominant Land Cover by Subwatershed (2005)

Sub-Basin Group	Receiving Body	Dominant Land Covers										
		Urban		Golf-Course	Seed Corn[1]	Truck crops[1]	Pineapple[1]	Fallow[1]	Scrub/Shrub	Grassland	Forest	Other Covers
		Civilian	Military									
1	Waikele Str.	X		X	X							
2	Waikele Str.				X	X						
3	Waikele Str.			X			X					
4	Waikele Str.	X										
5	Waikele Str.		X				X					
6	Waikele Str.		X									
7	Waikele Str.		X				X					
8	Waikele Str.						X				X	
9	Ekahanui-Huliwai Gulch			X			X	X			X	
10	Poliwai-Manuwaiahu Gulch						X				X	
11	Kipapa Str.					X	X				X	
12	Kipapa Str.	X										
13	Kipapa Str.	X										
14	Kipapa Str.	X										
15	Kipapa Str.					X	X				X	
16	Kipapa Str.										X	
17	Kipapa Str.										X	
18	Waikakalaua Str.	X		X						X	X	
19	Waikakalaua Str.	X										
20	Waikakalaua Str.										X	
Watershed-wide Areas (mi^2)		9.1		0.7	1.3	1.5	5.7	0.6	4.3	1.5	21.3	0.2

[1]Other covers category includes Wetland, Water, Bare land and pasture

A7. Changes in Land Use over Time

Table A.6 and Figure 2.3 estimate the area of different land covers present in the study area around 1980. This land cover characterization was created by using a GIS dataset depicting pineapple and sugar cane production areas circa 1980 (Hawaii, 1980) to modify the 2005 Land Cover dataset. Pineapple and sugar cane areas were added to the dataset if they were not shown in the 2005 C-CAP data as evergreen forest, scrub/shrub, water, wetland, and on a case-by-case basis in areas of grassland and impervious surface; these areas were assumed to have not been added with the removal of pineapple or sugar cane. Chapter 2 discusses these results in detail.

Table A.6: Comparison of Area by Land Use Classification (1980 vs. 2005)

Land Cover Group		1980 Area (mi^2)	2005 Area (mi^2)
Roadway and Parking Overlay	Impervious Surfaces Non-Travelled	2.3	3.7
Roadway and Parking Overlay	Impervious Surfaces Travelled	1.2	1.7
Urban Grass		2.2	3.6
Golf Course		0.5	0.7
Agriculture Overlay	Fallow	< 0.1	0.6
Agriculture Overlay	Pasture	< 0.1	< 0.1
Agriculture Overlay	Truck Crop	< 0.1	1.5
Agriculture Overlay	Seed Corn	0.0	1.3
Agriculture Overlay	Sugarcane	9.2	0.0
Agriculture Overlay	Pineapple	4.4	5.7
Scrub/Shrub		4.1	4.3
Grassland		1.1	1.5
Bare Land		< 0.1	< 0.1
Forest		21.0	21.3
Wetland and Water		0.02	0.02
Total Watershed		**46.2**	**46.2**

A8. Paved and Unpaved Roads

GIS datasets were used to quantify the length (and area) of non-agricultural roads within each subwatershed (Tables A.7 and A.8). The GIS roadway datasets[1] include agricultural roads but

[1] Pavement roadways = City and County of Honolulu and State DOT right-of-ways intersected with C-CAP impervious area plus a manual delineation of parking lot areas. Un-Paved Roadways = State of Hawaii 'othroads_n83.shp' dataset extracted from the USGS 1983 DLGs; all 'Pavement roadways' were removed from this dataset.

this class is not complete and the agricultural road areas were removed from the datasets and their area and length calculated separately (see Section A9).

A9. Agricultural Roads

The length of agricultural roads is not specifically used in the erosion yield estimates (Appendix C) but they are discussed here because the information may be helpful in future sediment management planning.

The length and area of agricultural roads were estimated from typical road densities for a given crop type, for both 1980 and 2005 land use areas (Table A.9). The crop-road density relationships are from investigations completed by University of Hawaii researchers in the 1970s (El-Swaify and Cooley, 1978 and El-Swaify, 1980) and from GIS processing of orthophotos of crops that were not included in this literature. In the University of Hawaii studies, the road coverage for sugar cane and pineapple fields varied from 0 to 5% and 13 to 17% of the basin area, respectively. The highest road densities were found for truck crops which tend to have smaller plot areas and a tighter road network around them. Seed corn and pineapple had similar, moderate road densities; sugar cane and other agricultural uses had relatively low road densities. An access road in an agricultural field near Manuwaiahu Gulch is shown on Photos A.9 and A.10.


Photos A.9 and A.10: An access road through an agricultural field near Manuwaiahu Gulch that was recently converted from pineapple to diversified crops (left, August 2, 2011) and the same road from the air under pineapple production (2005)

Table A.7: 1980 Non-Agricultural Roadway Length and Area by Subwatershed[3]							
		Pavement Roadways			Un-Paved Roadways		
Sub-Basin Group	Sub-Basin Area (acres)	Roadway Area (acre)	approx. length (miles)[1]	Length in miles per 100 acre of SB area	Roadway Area (acres)	approx. length (miles)[2]	Length in miles per 100 acre of SB area
1	1865.3	43.4	11.9	0.6	24.2	13.3	0.7
2	964.8	0.0	0.0	0.0	22.8	12.5	1.3
3	1268.0	10.3	2.8	0.2	18.9	10.4	0.8
4	333.4	40.6	11.2	3.4	1.7	1.0	0.3
5	1433.8	219.7	60.4	4.2	18.1	9.9	0.7
6	254.4	55.9	15.4	6.0	0.0	0.0	0.0
7	1496.8	187.4	51.5	3.4	9.7	5.4	0.4
8	2932.0	6.9	1.9	0.1	44.9	24.7	0.8
9	2886.3	4.8	1.3	0.0	13.1	7.2	0.2
10	2501.3	6.8	1.9	0.1	31.2	17.2	0.7
11	1762.1	15.3	4.2	0.2	46.7	25.7	1.5
12	382.5	71.5	19.7	5.1	1.0	0.5	0.1
13	806.1	84.2	23.2	2.9	0.0	0.0	0.0
14	1424.9	32.7	9.0	0.6	0.3	0.1	0.0
15	1634.0	0.1	0.0	0.0	20.5	11.2	0.7
16	1282.3	0.0	0.0	0.0	0.1	0.1	0.0
17	2645.8	0.0	0.0	0.0	0.0	0.0	0.0
18	1699.6	62.4	17.2	1.0	21.1	11.6	0.7
19	674.5	44.9	12.4	1.8	0.5	0.3	0.0
20	1311.4	0.0	0.0	0.0	0.0	0.0	0.0
All Study Area	29559.2	887.0	243.9	0.8	274.9	151.2	0.5

[1] Assumed 30 feet width for pavement roadways

[2] Assumed 15 feet width for un-paved non-agricultural roadways

[3] Since all major existing paved roads were assumed to also have existed in 1980, the estimate of 1980 pavement roadway length is most likely higher than what really existed at the time.

Table A.8: 2005 Non-Agricultural Roadway Length and Area by Subwatershed							
Sub-Basin Group	Sub-Basin Area (acres)	Pavement Roadways			Un-Paved Roadways		
		Roadway Area (acre)	approx. length (miles)[1]	Length in miles per 100 acre of SB area	Roadway Area (acres)	approx. length (miles)[2]	Length in miles per 100 acre of SB area
1	1865.3	112.6	31.0	1.7	32.4	17.8	1.0
2	964.8	0.0	0.0	0.0	22.8	12.5	1.3
3	1268.0	11.9	3.3	0.3	18.9	10.4	0.8
4	333.4	52.6	14.5	4.3	1.8	1.0	0.3
5	1433.8	219.8	60.4	4.2	18.1	9.9	0.7
6	254.4	55.9	15.4	6.0	0.0	0.0	0.0
7	1496.8	187.4	51.5	3.4	11.2	6.2	0.4
8	2932.0	6.9	1.9	0.1	44.9	24.7	0.8
9	2886.3	4.8	1.3	0.0	13.6	7.5	0.3
10	2501.3	7.0	1.9	0.1	31.5	17.3	0.7
11	1762.1	18.7	5.2	0.3	54.8	30.1	1.7
12	382.5	71.7	19.7	5.2	1.1	0.6	0.2
13	806.1	126.8	34.9	4.3	0.0	0.0	0.0
14	1424.9	280.6	77.2	5.4	0.3	0.1	0.0
15	1634.0	0.1	0.0	0.0	20.5	11.2	0.7
16	1282.3	0.0	0.0	0.0	0.1	0.1	0.0
17	2645.8	0.0	0.0	0.0	0.0	0.0	0.0
18	1699.6	63.8	17.5	1.0	21.1	11.6	0.7
19	674.5	81.1	22.3	3.3	0.5	0.3	0.0
20	1311.4	0.0	0.0	0.0	0.0	0.0	0.0
All Study Area	29559.2	1301.7	358.0	1.2	293.5	161.4	0.5

[1] Assumed 30 feet width for pavement roadways

[2] Assumed 15 feet width for un-paved non-agricultural roadways

Table A.9: Agricultural Road Area Estimates by Crop from 1980 and 2005			
Crop	**Road Density by area (unitless)**	**Roadway Area from Road Density (mi^2)**	
		Year 1980	**Year 2005**
Fallow	0.07[1]	0.0	0.0
Pasture	0.01[2]	0.0	0.0
Truck Crop	0.25[3]	0.0	0.4
Seed Corn	0.15[3]	0.0	0.2
Sugarcane	0.05[4]	0.5	0.0
Pineapple	0.17[4]	0.8	1.0
Agricultural Road Area in Waikele Watershed (mi^2)		1.3	1.6
Agricultural Road Length in Waikele Watershed (mi)[5]		335	425

[1] Varies dramatically depending on prior crop and thoroughness of abandonment, assumed 7%
[2] Varies, assumed 1%
[3] Estimated from 2005 Orthophotos
[4] El-Swaify and Cooley (1978)
[5] Assumes 20 foot width for un-paved agricultural roadways

APPENDIX B

APPENDIX B: FIELD RECONNAISSANCE OF WAIKELE WATERSHED

The photos in Appendix B are from a field reconnaissance on August 1 and 2, 2011, including a helicopter flight over the Koolau Ranges and Waikakalaua and Kipapa Streams and ground inspections of the two streams.

The photos in the Appendix are organized by the major tributary watersheds. The exact position where the photographs were taken is generally not known but some are roughly described by landmarks.

Photo B1: Tortuous channel of Waikakalaua Stream incised in bedrock.

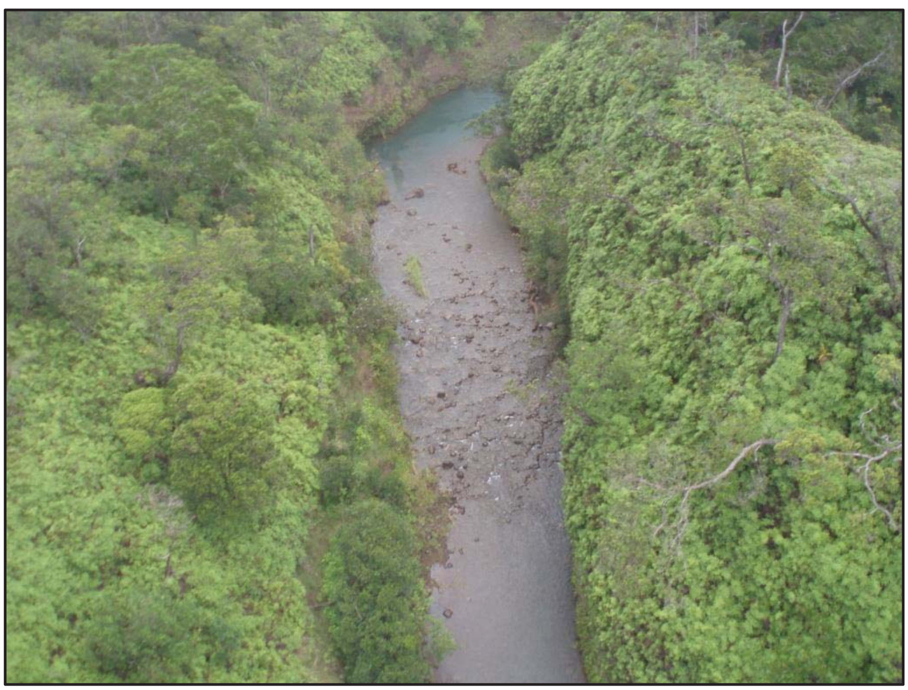


Photo B2: Bed material and bend in bedrock of Waikakalaua Stream. View upstream.

Photo B3: Partially re-vegetated landslide on north valley wall. Bedrock in headwall.

Photo B4: View of right bank of Waikakalaua Stream at upstream end of Mililani Town. Bank appears to be saprolite.

Photo B5: View of bed material (saprolite) in Waikakalaua Stream in Mililani Park.

Photo B6: Upstream view of Waikakalaua Stream from bridge near junction with upper Waikele Stream.

Photo B7: Headwall of upper Kipapa Stream near crest of Koolau Range. Debris slides/flows visible.

Photo B8: Headwall of upper Kipapa Stream showing debris slides.

Photo B9: View of open slope debris slide in upper Kipapa Watershed.

Photo B10: View of debris slide/bedrock exposure in upper Kipapa Watershed.

Photo B11: View of bend in upper Kipapa Stream. Flow left to right.

Photo B12: View of bed material and vegetation on upper Kipapa Stream.

Photo B13: View upstream on Kipapa Stream, upstream of USGS gage.

Photo B14: View to eroding left bank (alluvial deposit) and floodplain.

Photo B15: View of coarse bed and bar material on Kipapa Stream, about 0.5 miles upstream of USGS gage.

Photo B16: View up the Kipapa Valley towards the Koolau Range.

Photo B17: View of Kipapa Gulch and Oahu Plain, looking downstream towards Pearl Harbor.

Photo B18: View of Kipapa Gulch and Oahu Plain, looking downstream towards Pearl Harbor.

Photo B19: View of west bank of gulch showing exposed bedrock and soils.

Photo B20: View across Kipapa Gulch to Mililani Town; agricultural fields and native surfaced road in foreground.

Photo B21: View of native-surfaced roads on Oahu Plain.

Photo B22: View of Upper Waikele Stream from bridge on Wheeler Field at junction with Waikakalaua Stream.

Photo B23: Upstream view of upper Waikele Stream at crossing near Wheeler Stables.

Photo B24: View downstream on upper Waikele Stream (towards culvert) in vicinity of USGS gage.

Photo B25: Upstream view of bed material on upper Waikele (saprolite exposure).

Photo B26: View of erosion by surface runoff from bedrock exposure at lookout in Kolekole Pass.

Photo B27: View of agricultural fields, field roads on west side of Waikele Stream.

Photo B28: View to north (Waianae Range in left background) of agricultural fields on west side of Waikele Stream.

APPENDIX C

APPENDIX C: PROCEDURES FOR CALCULATING FINE SEDIMENT YIELDS FOR THE SIGNIFICANT EROSION PROCESSES

C1. Introduction

This appendix describes background studies and the assumptions and procedures adopted to calculate annual fine sediment yield (AFSY) from the significant erosion processes in the Waikele Watershed. Some of the AFSY calculations are based on erosion studies completed on Oahu or in the Waikele Watershed; some processes have not been studied and yields are roughly estimated. Fortunately, the more significant processes – landslides, agriculture, and bank erosion – have the best-supported calculation procedures.

The quantities of fine sediment provided to streams by the various erosion processes often are calculated from a volume of sediment eroded, a percentage of clay and silt in the eroded soils, a delivery ratio, and the attrition during transport that may increase the volume of clay and silt through breakdown of coarser particles. Sources of information for soil characteristics, such as silt and clay content and bulk densities, are described in the next section. Attrition estimates are also discussed in Section C2; delivery ratios are discussed throughout the appendix.

This appendix describes the calculation procedures. The results of the AFSY calculations for the tributary watersheds and the overall watershed are in Chapter 6 of the main report.

C2. Soil Characteristics

The gradation and the percentage of fine sediments are available for soils on the Schofield and Oahu Plains through the SURGO database. Unfortunately, there is little information on the soils in the upper elevations of the Ko'olau and Waianae Ranges where landsliding occurs, and none for the bank deposits along many of the streams, particularly the upper elevation step-pool and cascade stream types that are exposed to bank erosion and soil creep. The following sections discuss existing information about soil properties in these parts of the watershed.

Fine Sediment Percentages

Where suitable information is available, the percent fine sediment of eroded soils was defined from the soils database. Where such information is not available, it has been defined from other studies on Oahu. Hill *et al* (1998) quoted the following average percent fines for different soils in the North Halawa Watershed and they have been used for calculating fine sediment contributions from landslides, bank erosion, and soil creep:

- Hillslope soils: Average of 51% silt and clay
- Stream banks: Average of 12% silt and clay
- Stream bed: Average of 2% silt and clay

Soil Bulk Densities

Sediment yield is expressed as weight or weight per unit area; erosion from sediment sources is often initially calculated as a volume. Bulk densities for the eroded soils are required to convert erosion volumes to weights of fine sediment in the budget. Where information is available, soil bulk densities were determined from the soil database. Where it is not, bulk densities are assumed to be between 81 and 94 lbs/ft^3 or 1.3 and 1.5 Mg/m^3.

Attrition Contributions

Hill *et al* (1998) is the only study that considered attrition of eroded coarse particle soils as part of the fine sediment budget. They based their estimates of attrition for the soils in the North Halawa Valley on abrasion-mill experiments. The attrition (i.e. conversion to silt and clay) of sand and fine gravel sizes over a simulated 8 km of bed load transport ranged from 40% for the debris flow deposits, 52% for the channel bank sediments, and 36% for the bed material deposits.

Attrition has been incorporated in the sediment budget by adjusting the percent fines found in the original deposit to include additional production during transport, rather than by calculating the production of fine sediment separately for the volume contributed to streams. The overall grain size distributions for the various deposits are not known, but the percent fines quoted above have been roughly adjusted to include attrition of the sand and gravel component, as follows:

- Hillslope soils: Average of 71% silt and clay with attrition
- Stream banks: Average of 25% silt and clay with attrition
- Stream bed: Average of 7% silt and clay with attrition

C3. Shallow Landslides

Sources of Information

Peterson *et al* (1993) inventoried landslides in the Honolulu District from air photographs taken between 1940 (earliest available) and 1992, producing a 50-year history of landsliding. The Peterson *et al* report provided maps showing the distribution of landslides and a summary of saprolite landslide and debris slide/flow numbers, areas and volumes. Ellen *et al* (1993) provided further details on the distribution of landslide initiation points as part of their hazard analysis and included an analysis of annual debris slide initiation probabilities by slope class. An inventory of landslides for the 1991 and 1992 water years was prepared for the North Halawa watershed as part of sediment budget studies that evaluated highway construction impacts (Hill *et al* 1998). Given that the inventory is of short duration, that only moderate flood peaks occurred in these two years, and that the landslide occurrence and frequency is not tied to slope or other watershed characteristics, the prediction of AFSY from landslides was based on the Peterson *et al* (1993) and Ellen *et al* (1993) studies. They are described in more detail in the following subsections.

Debris Slides/Flows Erosion Rates

Ellen *et al* (1993) defined long-term regional weathering or erosion rates for the leeward slopes of the Ko'olau Range that were based on erosion of the original volcanic slopes and expressed as a function of annual rainfall. For a given subwatershed area, the annual rainfall can then be used to calculate the long-term average erosion rate. The erosion rate was then adjusted to a volume and the average number of landslides per unit area per year was calculated from the average landslide volume of 120 m^3. Typical annual slide frequencies in the upper slopes near the crest of the Ko'olau Range were about 3 to 4 slides per mi^2.

Ellen *et al* (1993) defined the probability that a debris slide/flow will initiate for a particular range of slopes from analysis of the 1,500 or so debris slides in the Pearson *et al* (1993) inventory; land surface slopes at the slide initiation points were calculated from a 10-m digital elevation grid. These probabilities were used to predict the numbers of slides per sq mi for the slope classes greater than 20^o based on the annual slide frequencies calculated from the regional erosion rate. These slide frequencies were then multiplied by the areas by slope class extracted for the subwatersheds.

The landslide numbers were multiplied by the average slide volume of Ellen *et al* (1993), a soil bulk density of 94 lbs/ft^3, a silt and clay percentage of 71%, and a delivery ratio. In the upper watersheds, a delivery ratio of 1 was adopted. Here, the landslides generally originate in narrow valleys and are carried directly to a stream. This assumption is consistent with the studies of Ellen *et al* (1993) and Hill *et al* (1998).

The calculated AFSY by slope class for the highest annual precipitation were applied to Subwatersheds (SW) 17 and 20 in the upper elevations of the Ko'olau Range where there are significant areas in the steepest slope class (Table C.1). The quoted AFSY are equivalent to an annual average of about 10 to 15 slides in the two subwatersheds.

Table C.1: AFSY from Debris Slides/Flows in Subwatersheds 17 and 20

Slope Class (%)	AFSY (tons per mi^2)	Subwatershed Area by Slope Class (mi^2)	
		SW 17	SW 20
< 40%	0	1.02	0.53
40 – 60%	190	1.16	0.29
60 – 80%	670	1.16	0.59
> 80%	1,400	0.79	0.64
Subwatershed AFSY (tons)		*2,100*	*1,300*

AFSY for the lower elevation subwatersheds (15, 16, and 18) in the Ko'olau Ranges were calculated by reducing the AFSY (tons per mi^2) in the above table by half to account for the lower annual rainfall and the less frequent slides/flows and then applying them to the observed distributions of slopes. Table C.2 summarizes the AFSY calculated by this procedure.

Table C.2: AFSY from Debris Slides/Flows in Subwatersheds 15, 16 and 18

Slope Class (%)	AFSY (tons per mi²)	Subwatershed Area by Slope class (mi²)		
		SW 15	SW 16	SW 18
< 40%	0	1.54	0.74	2.04
40 – 60%	85	0.61	0.68	0.42
60 – 80%	335	0.31	0.44	0.16
> 80%	700	0.07	0.14	0.03
Subwatershed AFSY (tons)		*200*	*300*	*100*

Table C.2 shows that debris slides/flows in the lower elevation subwatersheds provide far less fine sediment than in the upper elevation ones. This occurs because of the reduced yields but primarily because of the much smaller areas in the steepest slope class. The calculated AFSY are equivalent to about one to two slides or so, every year, in these subwatersheds.

Table C.3 estimates the AFSY from debris slides/flows for the subwatersheds in the upper Waianae Range (8 and 9) following the same procedures as Table C.2 but assuming the AFSY by slope class is reduced by half again to account for annual rainfall of about 40 to 60 inches.

Table C.3: AFSY from Debris Slides/Flows in Subwatersheds 8 and 9

Slope Class (%)	AFSY (tons per mi²)	Subwatershed Area by Slope class (mi²)	
		SW 8	SW 9
< 40%	0	3.07	3.33
40 – 60%	40	0.69	0.54
60 – 80%	170	0.50	0.41
> 80%	350	0.32	0.22
Subwatershed AFSY (tons)		*220*	*170*

The AFSY from slides/flows in Table C.3 is equivalent to an average of about 1 to 2 slides initiating in each subwatershed each year. The actual annual frequency of debris slides/flows in the Waianae Range has not been studied and is not known. Given that the calculated volumes in Table C.3 are not a very large component of the Waianae Tributaries sediment budget, a detailed study does not seem justified. Such a study might be considered as part of later, more detailed investigations.

Steep slopes occur in a few other subwatersheds, primarily along the valley walls of the Waikele and Kipapa Gulches. Slides do seem to occur on some of these steep slopes (refer to Appendix B) but they do not seem to contribute directly to streams and they have been ignored in this rapid budget. Further study might be considered as part of later, more detailed investigations.

Saprolite Landslide Erosion Rates

Peterson *et al* (1993) estimated that between 3 and 8 saprolite landslides occurred in the Honolulu District over the 50 years of their inventory, or about one per decade. Little is known of the factors that influence their distribution and estimates of the erosion from this process will be based on an average yield applied to subwatersheds with appropriate slopes and rainfall.

While rare, the saprolite landslides are capable of moving large volumes of sediment. Not all of these failures will be as large as the major debris flow down Kupaua Valley (46,000 yd^3 or 35,000 m^3) observed by Peterson *et al* (1993). Assuming that the average saprolite landslide has a volume of about 10,000 yd^3, that the bulk density is about 94 lbs/ft^3, and the percent silt and clay is 25% (including attrition), the annual fine sediment yield in the Honolulu District if one saprolite landslide occurs per decade would be about 1,300 tons.

The Honolulu District has a total land area of 85.7 mi^2 and an estimated steep land area of 30 mi^2. On this basis, the annual yield for saprolite landslides would be 40 tons per mi^2 of steep land, or considerably less than that from debris slides and flows (refer to Table C.1). This rate would be applied to those subwatersheds with the highest annual rainfall and the steepest slopes or only to Subwatersheds 17 and 20. It is assumed that this landslide process does not occur in the Waianae Range where annual rainfall is much less.

Given the rarity of the saprolite landslides, it is unlikely that it will be observed in the upper elevations of the Ko'olau Range in the Waikele Watershed. However, should one occur, it would dominate fine sediment production for many years because of its very large size.

C4. Soil Creep

Sources of Information

There does not appear to be any long-term observations of creep rates on Oahu or in the Waikele Watershed. Hill *et al* (1998) attempted short-term measurement of creep as part of their sediment budget study in the North Halawa Watershed. Construction damage to some of their sites resulted in them adopting a typical rate of 0.004 m/year over a soil depth of 0.5 m. This typical rate was from Lewis (1976) and Saunders and Young (1983) and it has been adopted for this study.

Adjusting the above rate and soil depth to US standard units and to include soil creep on both banks, results in a typical annual creep of 10 tons per mile of stream. It is assumed that all the creep erosion is delivered to a stream and that about 25% of the yield is fine sediment when attrition is included, providing an AFSY of 2.5 tons per mile of stream.

Application to Waikele Watershed

Soil creep is expected to be most significant in narrow valleys where colluvial slopes are close to both banks of the stream. This primarily occurs in the Ko'olau and Waianae Ranges in the cascade, step-pool and, to some extent, plane-bed stream types. The AFSY quoted above is adjusted to the different stream types in Table C.4.

Table C.4: Adjusting Soil Creep Erosion by Stream Type

Stream Type	Adjustment	AFSY (tons per mi)	Explanation
Cascade	0.75	1.9	Reduced to account for bedrock valley walls
Steep-pool	0.75	1.9	Reduced to account for bedrock valley walls
Plane-bed	0.5	1.3	Reduced because stream is often distant from valley walls
Pool-riffle	0.25	0.6	Stream distant from valley walls

Creep is a much less significant source of sediment than the stream bank erosion discussed in the next section.

C5. Stream Banks

Sources of Information

There are only two studies of stream bank erosion on Oahu and only one has calculated fine sediment yield. Hill *et al* (1998) estimated fine sediment yield from bank erosion along 10 miles of North Halawa Stream, quoting results for net change of the channel bank volume, based on surveyed deposition and erosion. The other study, by the USGS, repeated cross section surveys on Waikele and Kipapa Streams annually from 2007 to 2010 (Izuka 2012). In this report, the bank erosion that occurred in the USGS study was calculated from the raw cross section data provided by the USGS.

North Halawa Stream Bank Erosion

As noted above, the bank erosion quoted by Hill *et al* (1998) is net of deposition. However, it is not known if the deposited sediments include the same portion of silt and clay as the eroded sediments. For this analysis, we have assumed that the sediments deposited within the channel near the banks have insignificant fine sediment content; consequently, we have revised the fine sediment yield so that it only includes the erosion component. Such an approach overestimates long-term AFSY from bank erosion but is acceptable for this preliminary analysis (Table C.5; following page).

North Halawa Stream has an average slope of about 7% over the study reach, and much of the stream falls into the step-pool category. Erosion was measured along North Halawa Stream for two years. The annual peak flow in 1991 had a return periods of between 10 and 25 years, and 1992 had a return period of about 2 years. Peak flow return periods are based on the recorded peaks at the North Halawa near Honolulu (16226200) gage. The average of the two years of observation was assumed to be roughly about the long-term average erosion rate for step-pool streams with watershed areas of about 4 sq mi.

Table C.5: Adjusted North Halawa Stream Bank Erosion

Water Year	Reach Length (mi)	Average Eroded Bank Area (ft^2)	Bank Retreat (feet) [1]	AFSY (tons per mi)	AFSY (with attrition) (tons per mi)
1991	10.1	1.4	0.5	24	48
1992	8.8	0.4	0.1	13	26
Averages		*0.9*	*0.3*	*19*	*38*

1. Assumes a bank height of 3 feet

USGS Bank Erosion Studies

As part of a suspended-sediment monitoring program in the Waikele Watershed, the USGS established 28 cross sections in 2007, primarily in the lower reaches of the Waikele and Kipapa streams on the Oahu Plain (Izuka 2012). The cross sections were primarily in pool-riffle and plane bed stream types. During the 2008 flood, monuments at some cross sections were lost to erosion and only a partial record of channel adjustments is available (Izuka 2012).

The stations were established to measure changes in bed storage. This study estimated bank retreat from one year to the next as the average retreat of the bank over its height at each cross section, by comparing consecutive surveys. Average bank erosion for different stream segments was calculated from all the available surveys for particular years and the results are reported in Table C.6.

Table C.6: Estimates of Average Bank Erosion for WY 2008, 2009 and 2010

Stream Type	Sites	Average Bank Retreat (ft)		
		2007-08	2008-09	2009-10
Lower Waikele Pool-Riffle	WK6, WK5, WK4, WK3	0.4	12	0.1
Waikakalaua Pool-Riffle	WK2	0.2	2	< 0.1
Upper Waikele Pool-Riffle	WK1	Site affected by downstream culvert		
Kipapa Pool-Riffle	K1 & K2	< 0.1	0.9	0

The measured average bank retreats vary from year to year in response to the magnitude of peak flows and from site to site in response to channel size, bank materials, bed materials, peak flows, and other factors that affect erosion. Table C.7 (following page) summarizes the approximate return period of the annual peak flow for the water years listed in Table C.6. Waikakalaua Stream (Site WK2) is not gaged and return periods for the peak flows were assumed to be the same as those for Kipapa Stream.

The lower peak flow return periods for Kipapa and Waikakalaua Streams – compared to Waikele Stream – help to explain the much lower bank retreat observed at sites on these two streams when compared to lower Waikele Stream.

Table C.7: Return Periods for Peak Flows for Bank Erosion Sites

Stream Gauge	Sites	Return Period by Water Year (WY)		
		2007-08	2008-09	2009-10
Waikele at Waipahu 16213000	WK6, WK5, WK4, WK3	5	100 to 500	< 2
Waikakalaua [1]	WK2	< 2	5	< 2
Waikele at Wheeler Field 16212601	WK1	Site affected by downstream culvert		
Kipapa near Wahiawa 06212800	K1 & K2	< 2	5	< 2

1. Ungaged; assumed to have the same return periods as the Kipapa gage

Combining Tables C.6 and C.7 suggests that the 100-year average bank retreat is about 12 feet, the 5-year bank retreat is about 0.6 feet and retreat is less than 0.1 feet for return periods less than 2 years. Table C.8 estimates the total annual retreat over a 100-year period, adopting a log-linear relationship to interpolate erosion rates at intermediate return periods and assuming bank retreat is negligible for return periods less than 2 years.

Table C.8: Estimating Annual Erosion Rates from Return Periods

Return Period	# of occurrences in 100 years	Average Erosion Rate (feet)	Total Erosion (feet)
100	1	12	12
50	2	6	12
25	4	3	12
5	20	0.6	12
2	23	0.1	2.3
< 2	50	0	0
Total	100		50.3

Based on Table C.8, the average annual bank erosion rate along the pool-riffle and plane bed reaches would be about 0.5 feet. Assuming the banks are 4 feet high, bulk densities of the bank material[1] are 75 lbs/ft^3 and that 25% of the bank soil consists of silt and clay (including attrition), the AFSY would be about 100 tons per mile of stream (including both banks). Such an

[1] Bulk densities reported by Izuka (2012) were reported as 1.1 ± 0.2 Mg/m3 (71 ± 13 lbs/ft3) for bed sediments. A value of 75 lbs/ft^3 was used for calculations performed for bank material in a draft version of this report prior to the USGS's publishing of Izuka (2012). The two values are considered to be within an acceptable level of agreement with one another.

estimate is thought to be appropriate for the most downstream reaches of Waikele and Kipapa Streams, where flows and channel dimensions are greatest and banks are erodible.

Application to the Waikele Watershed

It is a common observation that average bank erosion rates increase with channel width, watershed area, peak flow or other measures of stream size (Brice 1982; Hooke 1980). There is broad variation of observed rates around any general relationship, depending on stream types, bank materials and other factors. For instance, Brice (see also Melville and Coleman 2000) observed that bank erosion rates were typically about 1% of channel width, but varied from 0.5 to 5% depending on channel type. Hooke (1980) identified a trend over a very broad range of watershed areas where the bank erosion rate was about proportional to the square root of watershed area.

Consequently, some adjustments to the previous analyses are required to apply the bank erosion observed in the lower reaches of the Waikele Watershed to stream segments in the upper watershed. It is easiest to adjust bank erosion rates with watershed areas. Adopting the Hooke equation, where bank erosion increases as the square-root of watershed area, and calculating the coefficient for pool-riffle and plane bed stream types from the annual erosion rate above and the watershed area for the cross sections (about 30 sq mi), the AFSY for pool-riffle and plane bed stream types will be:

$$AFSY_{bank} = 18 \times A^{0.5}$$

Adopting the same equation but calculating the coefficients from the annual rate and watershed area for North Halawa Stream, the equation for step-pool stream types will be:

$$AFSY_{bank} = 19 \times A^{0.5}$$

In the above equations, AFSY is expressed in tons per stream mile and A is watershed area in sq mi. Given the similarity of the constants, the equation was applied to all stream types, including cascade type ones, with a constant of 18. The AFSY includes attrition of the bank materials during transport and assumes a delivery ratio of 1. The above equations are expected to predict conservatively high estimates of bank erosion since they do not account for less erodible banks and more bedrock exposures in the upper stream reaches.

C6. Surface Erosion from Natural Sources

The potential natural sources of surface erosion will be from exposure of soils on landslide scars and along feral pig and other wild animal trails and wallows. Fire is another potential natural source but has not occurred recently in the Waikele Watershed.

Landslide Scar Erosion

Erosion from landslide scars has not been measured or studied on Oahu. Consequently, the average erosion is calculated from the annual slide/flow frequency, the typical area exposed by the landslide, and an erosion rate appropriate for exposed soil. Annual frequencies of debris slides/flows were back-calculated from the erosion volumes reported in Tables C.2 to C.3 and multiplied by the average area of 3,100 ft^2 (Peterson *et al,* 1993). Erosion rates for exposed soils on the steep slopes where landslides occur have not been measured. Erosion rates for bare soils on moderate slopes quoted in El-Swaify (1990) average 350 Mg/ha (100,000 tons per mi^2). Such rates are equivalent to a denudation rate or soil loss of around 25 mm/year, depending on assumptions about bulk density, and would result in rapid exhaustion of the erodible soil. Consequently, we have assumed that erosion will only occur for two years on each scar. Results for the subwatersheds with landslides are quoted in Table C.9.

Table C.9: AFSY from Landslide Scars

Subwatershed	# Slides	Area (ft^2)	AFSY (tons)
8	2	6,200	44
9	1	3,100	22
15	2	6,200	44
16	2	6,200	44
17	15	47,000	330
18	1	3,100	22
20	10	31,000	220
Totals	*33*	*2.4 acres*	*730*

The AFSY for each subwatershed with landslides assumes 71% of the eroded material is fine sediment and that all of it is delivered to a stream. The above estimates may be too high but they will also help account for surface erosion that might occur beneath vegetation in the steep slopes in the upper watersheds.

Feral Animal Disturbance

While there have been a number of studies of feral pigs and ground disturbance by pigs and other wild animals in the conservation lands on Oahu, the typical area disturbed and the rate of erosion of the exposed soils have not been reported or measured. A general impression is that these disturbed areas are a very small portion of the total watershed area and that much of the observed disturbance occurs on relatively low slopes adjacent to streams where erosion rates are less than on steeper slopes.

In the absence of any other information, we have assumed that the disturbance is confined to Subwatersheds 17 (Upper Kipapa) and 20 (Upper Waikakalaua), and the AFSY is equal to one-half of the AFSY from the landslide scars in Table C.9. These rates would imply disturbance areas of one-half to one acre, depending on the assumed erosion rates for the disturbed soils.

C7. Surface Erosion from Human-Modified Sources

Introduction

This section provides estimates of the annual fine sediment yields from: 1) urban residential or commercial areas; 2) agricultural fields; and 3) active military reserves. Roads are discussed separately in Section C.8.

Urban Residential and Commercial

The USGS measured annual suspended sediment loads from Mililani Town at their Mililani Storm Drain A at Mililani gage. The average annual load from this residential development was 26 tons per mi^2 from 2008-2010 and this has been adopted as an appropriate AFSY for all urban development, including residential and other development at Schofield Barracks and Wheeler Field. It has been further assumed that the entire load is silt and clay.

Agricultural Fields

The loss of sediment as a result of rainfall and runoff on agricultural lands has been studied extensively in Hawaii with the goal of conserving sediment for crop production and protecting downstream receiving bodies. Early studies conducted by the University of Hawaii (El-Swaify and Cooley, 1978 and 1980) measured sediment production from sugar cane and pineapple plantations by gaging flows and sediment at the outlet of small watersheds. Details are provided in El-Swaify and Cooley (1978) but the program measured yields from agriculture, including plantation roads, as a net of erosion and deposition within the fields.

Subsequently, El-Swaify (2002) estimated sediment production for upland taro and bulb onion crops, and other crop scenarios, by calibrating a RUSLE model to measured production from sugar cane and pineapple, and applying it to the cultivation practices for the other two crops. Sugar cane cultivation, which no longer occurs in Waikele Watershed, tended to have the lowest soil losses of the crops discussed above.

Table C.10 provides a range of annual soil losses estimated for the six crops currently grown in the Waikele Watershed based on the publications described above. There are no observations of soil loss from the truck crops and seed corn crops that were grown on about 30% of the agricultural area in 2005. These are assumed to have similar soil losses to the bulb onion crops, but further study would be needed to confirm this assumption.

Table C.10: Estimated Average Annual Soil Losses (AFSY) from Crops

Crop	USLE C-Factor	AFSY		Source
		Mg/ha	Tons/acre	
Fallow		~1	0.4	Assumed
Pasture	0.003 to 0.45	~ 1	0.4	Assumed

Truck Crop	0.3 to 0.45	3.8 to 8.0	1.7 to 3.6	Similar to bulb onions in El-Swaify (2002)
Seed Corn	0.4	3.8 to 8.0	1.7 to 3.6	Similar to bulb onions in El-Swaify (2002)
Sugar cane	0.11 to 0.16	1.2 to 2.5	0.5 to 1.1	El-Swaify (2000)
Pineapple	0.17 to 0.31	6.9 to 7.1	3.1 to 3.2	El-Swaify (2000)

Annual soil losses range from about 0.4 to 3.6 tons/acres. Equivalent denudation rates, assuming a bulk density of 75 lbs/ft^3 (based on the SSURGO database), are 0.12 to 1.0 mm, with the greatest rate being about 10 times the long-term erosion rate for Oahu.

When calculating AFSY, we have adopted the loss from the middle of the ranges for the crops provided in Table C.10 and have assumed that all this sediment is delivered to streams. We have also assumed that all the annual loss is silt and clay, although this is not evident from the various project reports.

Table C.11 compares soil losses for agriculture in 1980 and 2005 based on the areas of the six crop categories (Appendix A) and losses in Table C.10.

Table C.11: Agricultural Areas and Soil Loss: 1980 and 2005

Crop Type		1980 Area (mi^2)	2005 Area (mi^2)	1980 Soil Loss (tons)	2005 Soil Loss (tons)
Crop Types	Fallow	< 0.1	0.6	30	150
	Pasture	< 0.1	0.02	30	5
	Truck Crop	< 0.1	1.5	170	2,500
	Seed Corn	0.0	1.3	0	2,200
	Sugarcane	9.2	0.0	4,700	0
	Pineapple	4.4	5.7	8,900	11,500
Totals		**13.6**	**9.1**	**13,800**	**16,400**

As shown in Table C.11, the replacement of the relatively soil-conservative sugar cane crops with less soil-conservative truck and seed corn crops over the past 25 years has not only increased soil loss per unit area, but has increased the total soil loss from agricultural areas in Waikele Watershed, despite the smaller area that is now devoted to crops.

Military Training Areas

The military reservations near the Schofield Barracks that are actively used for training consist of the East Range and the West and South Range. Other military reservations within the Waikele Watershed do not appear to be actively used for training or other purposes. The East

Range, which is a maneuver area in the Ko'olau Range, lies adjacent to but north of Waikakalaua Stream. The West and South Ranges are east of Schofield Barracks and extend into the Waianae Range. A portion of these ranges lies in Subwatershed 8 and the total military reserve area in this subwatershed is estimated to be 0.66 sq mi. Inspection of this part of the watershed on recent aerial images showed removal of cover, buildings, and other features on about one-tenth of the total area or about 40 acres. Based on maximum soil losses of about 4 tons/acre from agriculture (Table C.10), we have estimated an annual AFSY of about 200 to 400 tons and assumed it is all fine sediment and all delivered to the stream. Given that this AFSY is only a small component of the sediment budget, more detailed investigations did not seem warranted.

C8. Surface Erosion from Roads

Introduction

Surface erosion from road networks is often difficult to quantify. Erosion occurs on the road surface, ditches, cut banks, and fill slopes and rates depend on climate, physical factors such as materials and slope, construction practices such as road surfacing, crowning, sloping, and culvert spacing, the time since construction, and also on traffic patterns and maintenance practices. Erosion analyses for road networks often rely on establishing a typical erosion rate for inactive or lightly-used road segments and then adjusting these to account for slope, traffic, maintenance practices, or other factors that might affect yield. Long-term predictions require an understanding of road use and maintenance over time, particularly for native-soil surfaced roads.

In the Waikele Watershed, surface erosion may occur from roads in agricultural fields, and from paved and non-paved roads in the various subwatersheds (Appendix A). Surface erosion from roads in agricultural fields is included in the soil losses quoted in Table C.10 and no further sediment contribution from these roads needs to be added to the budget. El-Swaify (2000; 2002) discussed the role of plantation roads in overall agricultural sediment production.

Unpaved Road Erosion

The Geography Department of the University of Hawaii (Alan Ziegler, project leader) has been examining hydrologic and erosion consequences of rural roads, trails, and paths in mountainous areas in Thailand and has published technical studies of road erosion processes under simulated rainfall on an unpaved (native-surfaced) road near Schofield Barracks (Ziegler *et al,* 2000; Ziegler and Sutherland, 2006). These studies provide a useful description of road erosion processes in Hawaii and also help establish typical erosion rates for native surface roads that are inactive or have light traffic.

Ziegler *et al* (2000) examined erosion from a moderately steep (> 5%) inactive road segment under intense simulated rainfall. The calculated erosion from their 1-hour study ranged from 12 to 16 tons per mile, depending on how loads were calculated from their reported data. Ziegler and Sutherland (2006) provided road surface erosion estimates prior to and following driving on a native-surfaced road, expressed per mm of runoff or rainfall excess. Calculating annual runoff volumes for the road from a suitable curve number, the annual erosion became 13 tons per mile prior to driving and 47 tons per mile after driving. Applying the erosion measured in the earlier study to the runoff volume resulted in an annual erosion of around 69 to 75 tons per mile, which is far too large for an annual rate on an inactive road. This is not surprising given the extreme rates adopted for the simulated rainfall.

MacDonald and Coe (2008) provide a summary of erosion rates from forest road surfaces in the United States. There is large variation in the summarized rates because of differences in slopes, surfacing materials, climate, traffic, and maintenance. However, the above quoted annual erosion yields fall within the broad range in the summary. It is particularly worthwhile to compare the quoted numbers above to a study by Reid and Dunne (1984) of annual yield from gravel-surfaced forest roads in Washington, which controlled for slope and traffic. Average sediment yields for light use roads were about 7 tons per mile from a gravel-surfaced road; that calculated post-driving by Ziegler and Sutherland (2006) was about 47 tons per mile. The yield from Ziegler and Sutherland is about 7 times greater, which is typical for roads on silty soils compared to gravel surfaces. The ratio of yield from light use to abandoned roads is about 7 times in Reid and Dunne; it is about 4 times from the Ziegler and Sutherland (2006) estimates.

Based on the above, we have adopted an erosion yield from unpaved road surfaces of 20 tons per mile. This assumes that the typical road yields at the post-driving rate about 25% of the time and at the pre-driving rate about 75% of the time, reflecting some use of the roads throughout the year. It also assumes that all of the eroded sediment is silt and clay.

Sediment delivery from the road surface to a stream depends on various factors, such as road cross slope and culvert spacing, and the distance to a stream, gradient, and the nature of the vegetation buffer. A preliminary estimate of the delivery ratio was developed from Coe (2006), who related the ratio to annual rainfall and the presence or absence of drainage structures. The calculated delivery was 68% for the Schofield and Oahu Plains, assuming an absence of engineered drainage structures. On this basis, the AFSY from unpaved roads was reduced to 14 tons per mile.

Paved Road Erosion

The paved roads included in Appendix A (Tables A.7 and A.8) are primarily residential roads in Mililani Town, Schofield Barracks, Wheeler Field and other residential areas. The sediment eroded from these roads and delivered to streams is accounted for in the AFSY from urban areas discussed earlier. Some erosion may be associated with ditches and cut slopes along highways and major thoroughfares in the watershed but it is difficult to separate these roads from other ones in the watershed. We have assumed that about 25 miles of the paved roads fall within the highway and major thoroughfare class. Reid and Dunne (1984) identified typical yields of about 3 to 4 tons per mile for these roads for a total yield of about 100 tons. This has been adopted as the AFSY from paved roads (non-residential) in the Waikele Watershed.

Appendix B: Hourly Single Event Flow Hydrographs and Sediment Pollutographs

APPENDIX B: Hourly Single Event Flow Hydrographs and Sediment Pollutographs

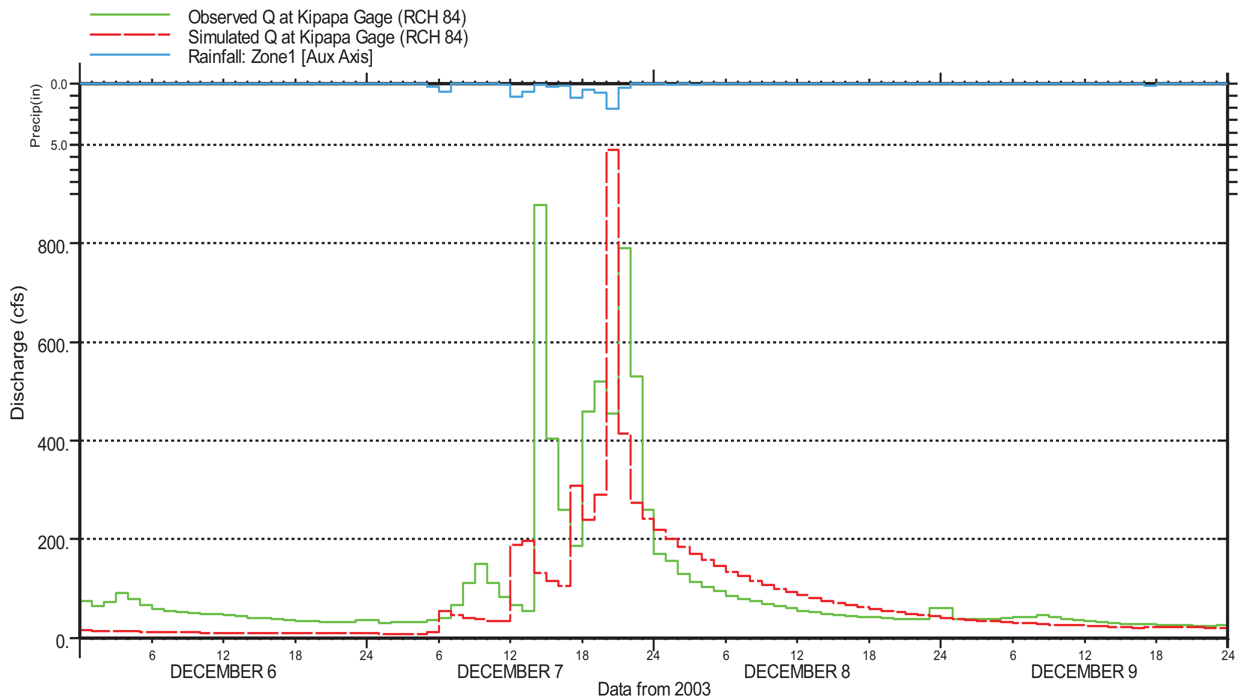


Figure B1: Hourly Stream Flow, Kipapa Stream near Wahiawa, December 7, 2003

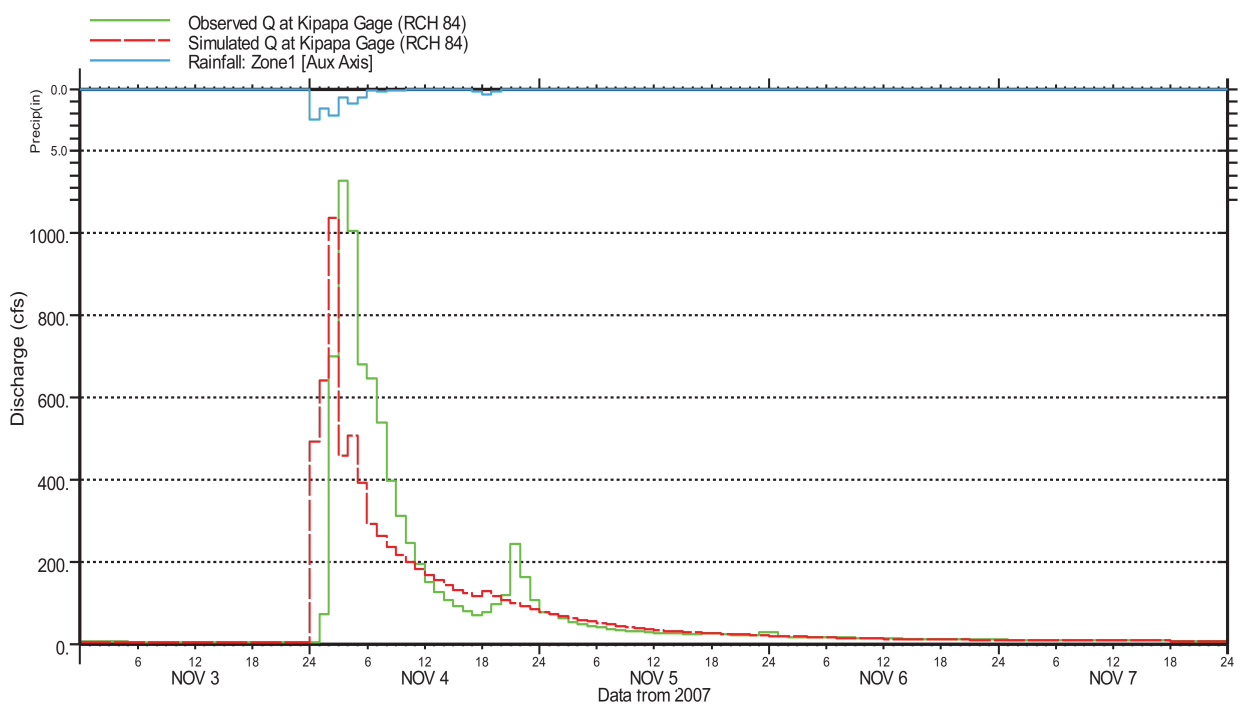


Figure B2: Hourly Stream Flow, Kipapa Stream near Wahiawa, November 4, 2007

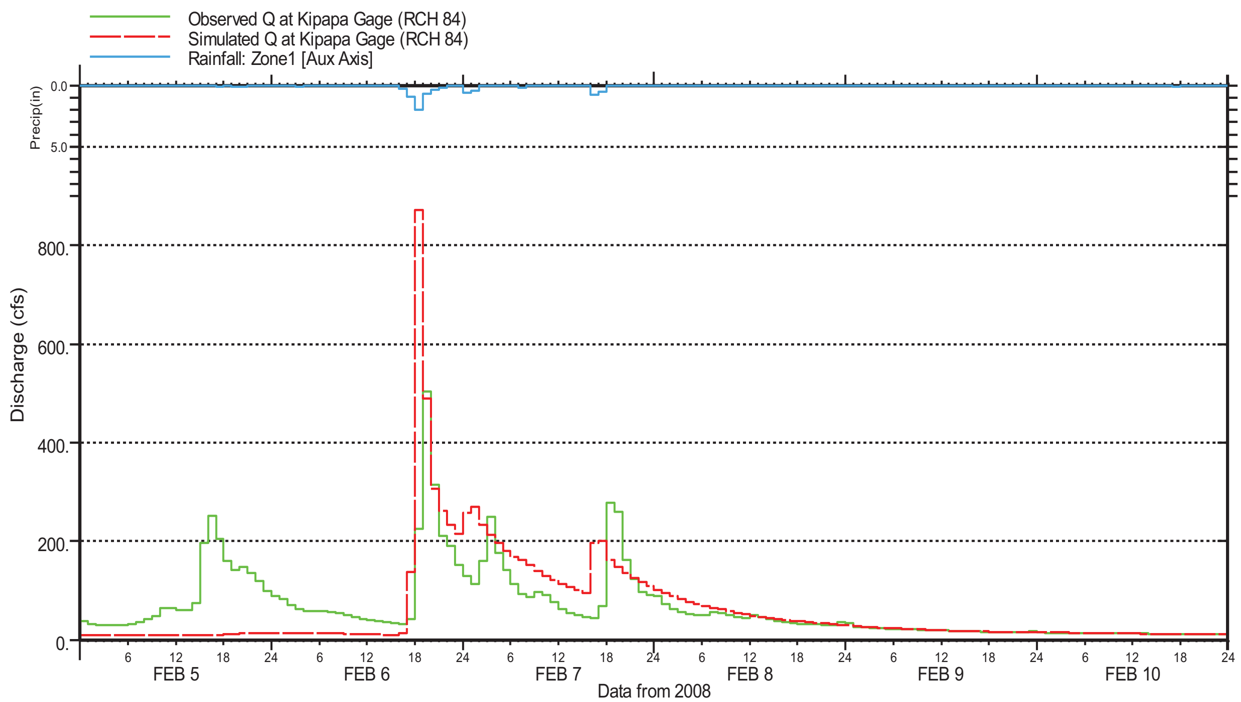


Figure B3: Hourly Stream Flow, Kipapa Stream near Wahiawa, February 7, 2008

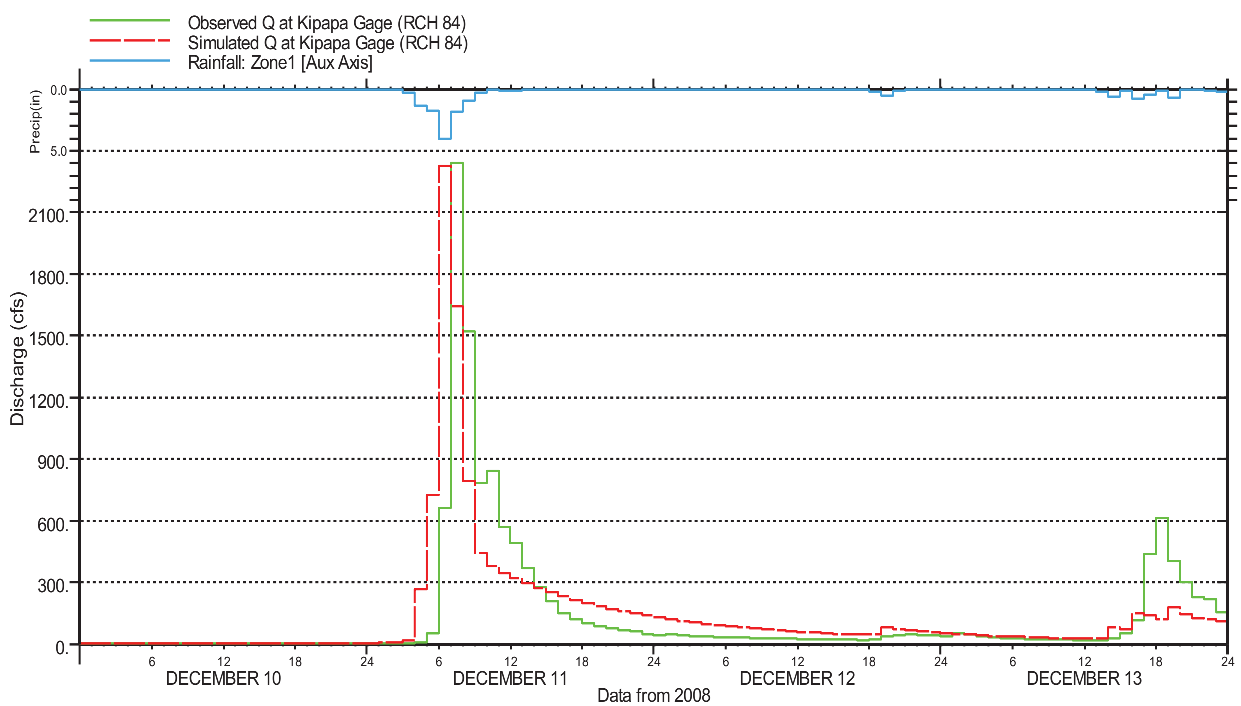


Figure B4: Hourly Stream Flow, Kipapa Stream near Wahiawa, December 11, 2008

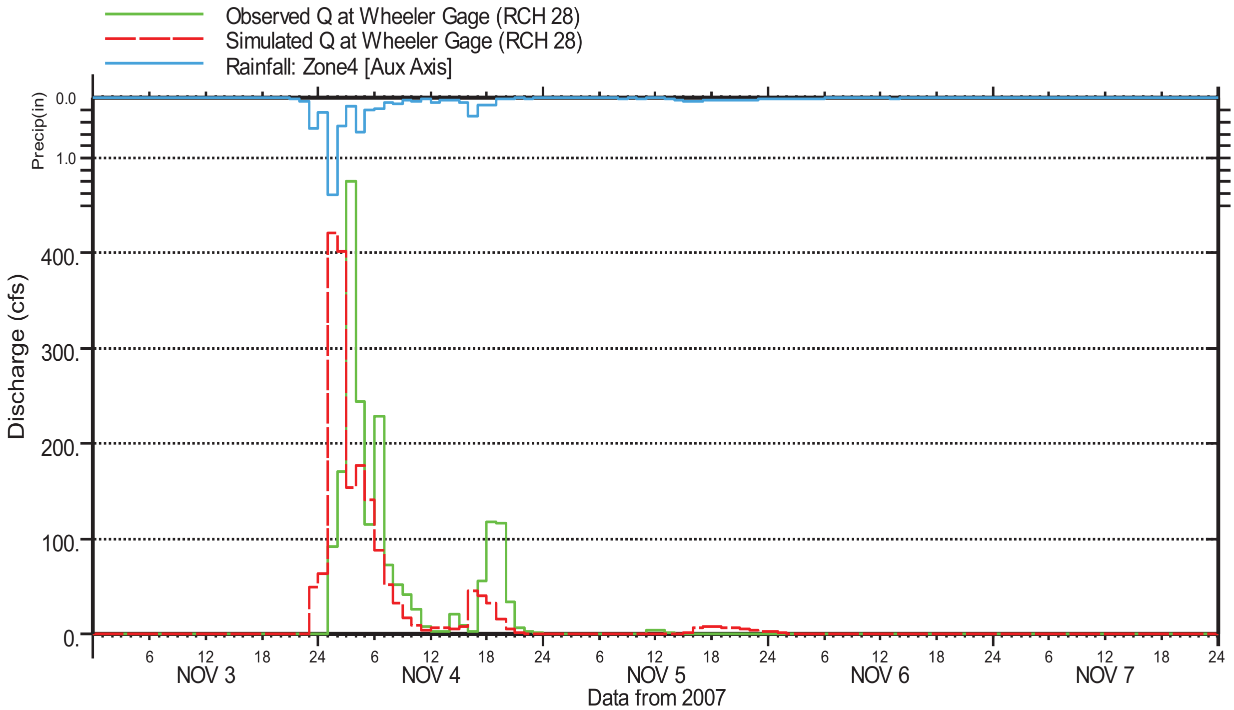


Figure B5: Hourly Stream Flow, Waikele Stream at Wheeler, November 4, 2007

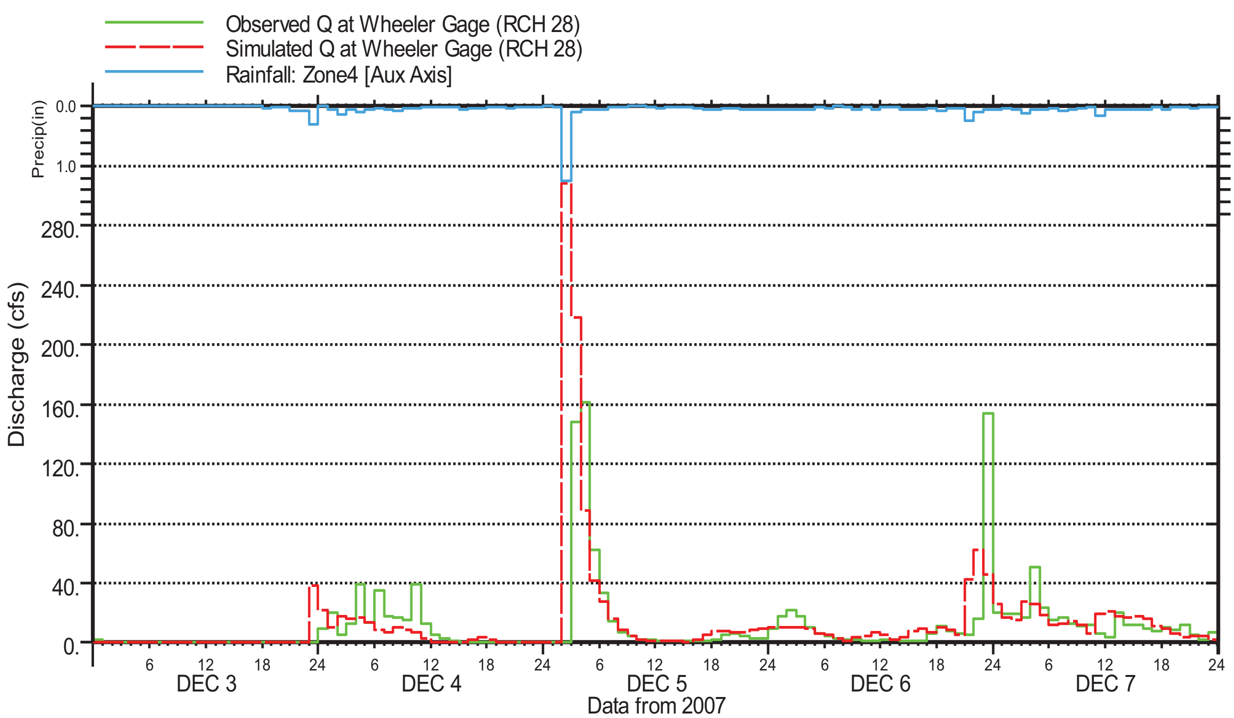


Figure B6: Hourly Stream Flow, Waikele Stream at Wheeler, December 5, 2007

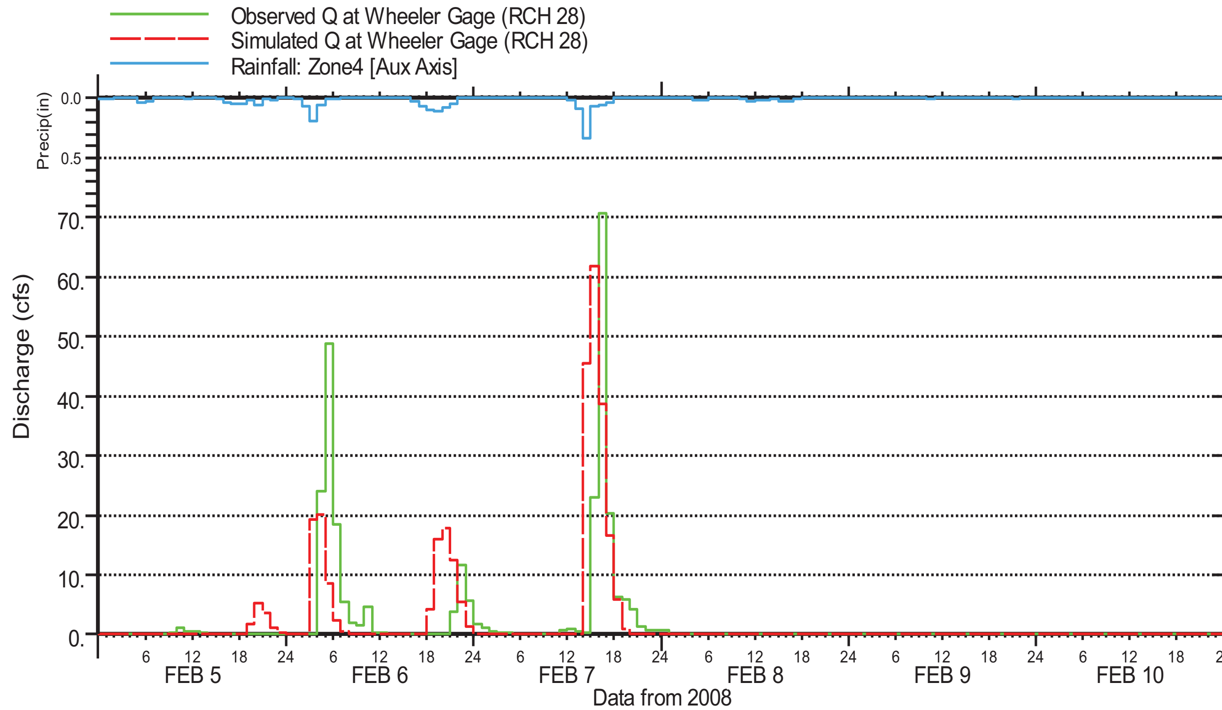


Figure B7: Hourly Stream Flow, Waikele Stream at Wheeler, February 7, 2008 Event

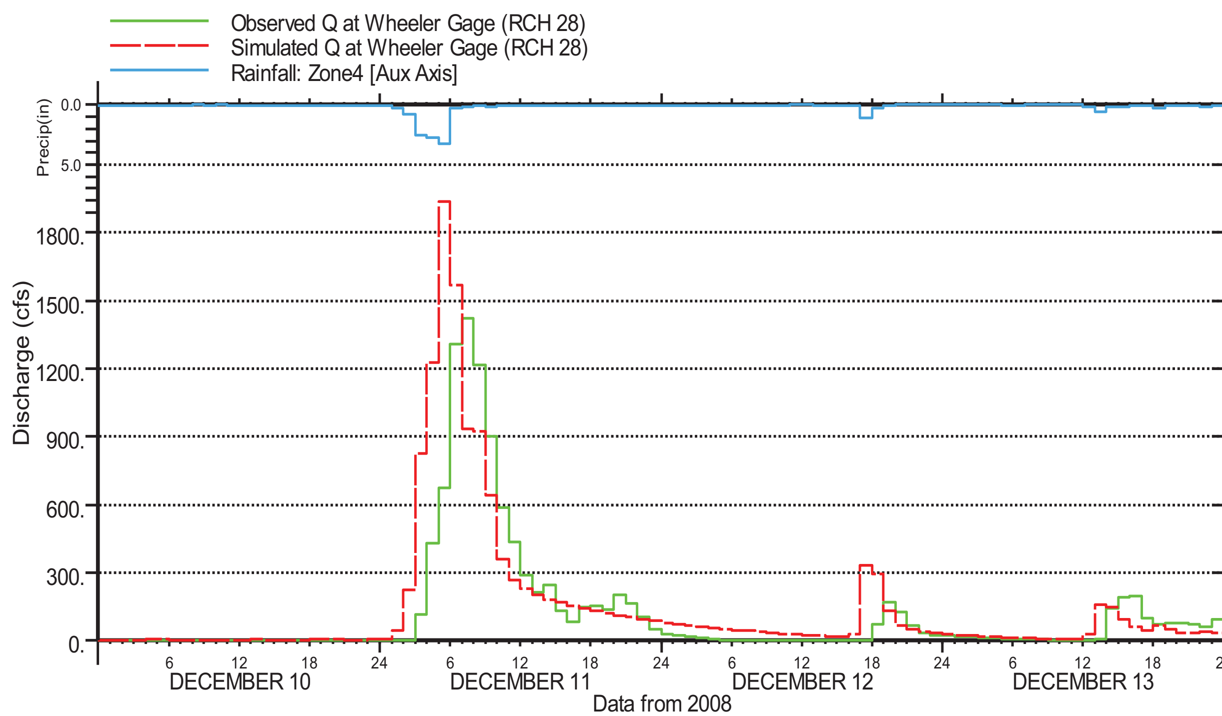


Figure B8: Hourly Stream Flow, Waikele Stream at Wheeler, December 11, 2008 Event

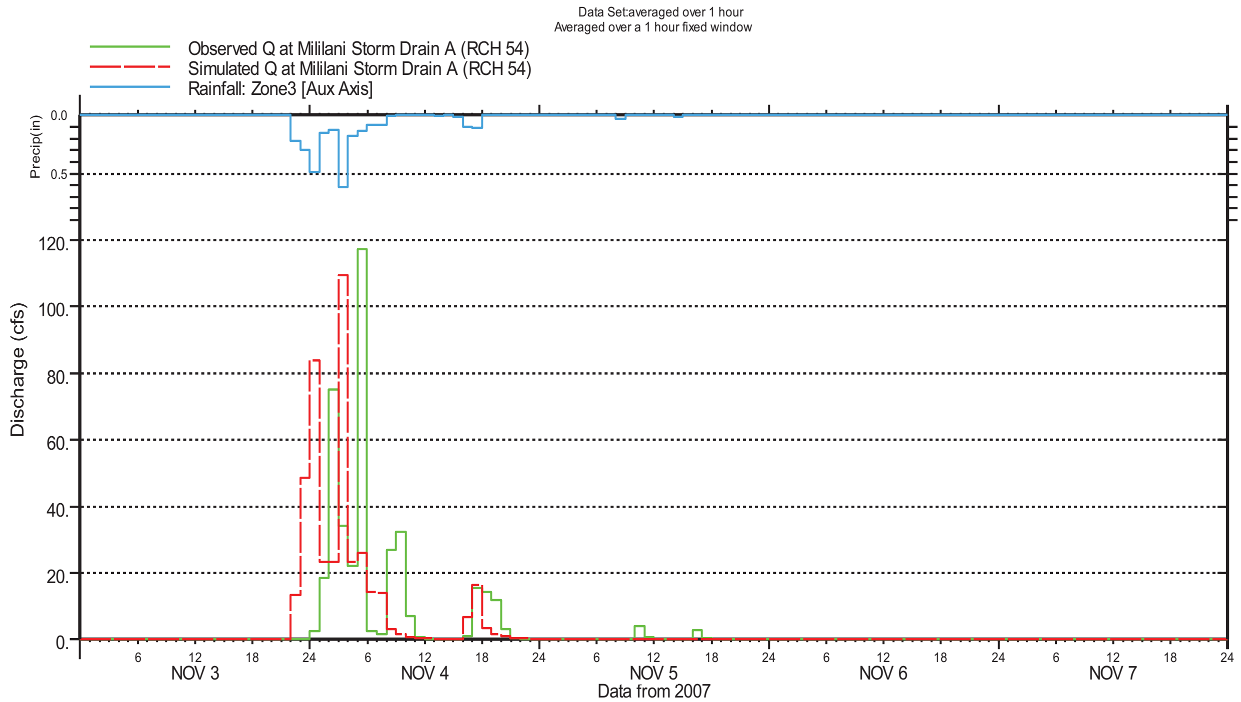


Figure B9: Hourly Stream Flow, Mililani Storm Drain A, November 4, 2007

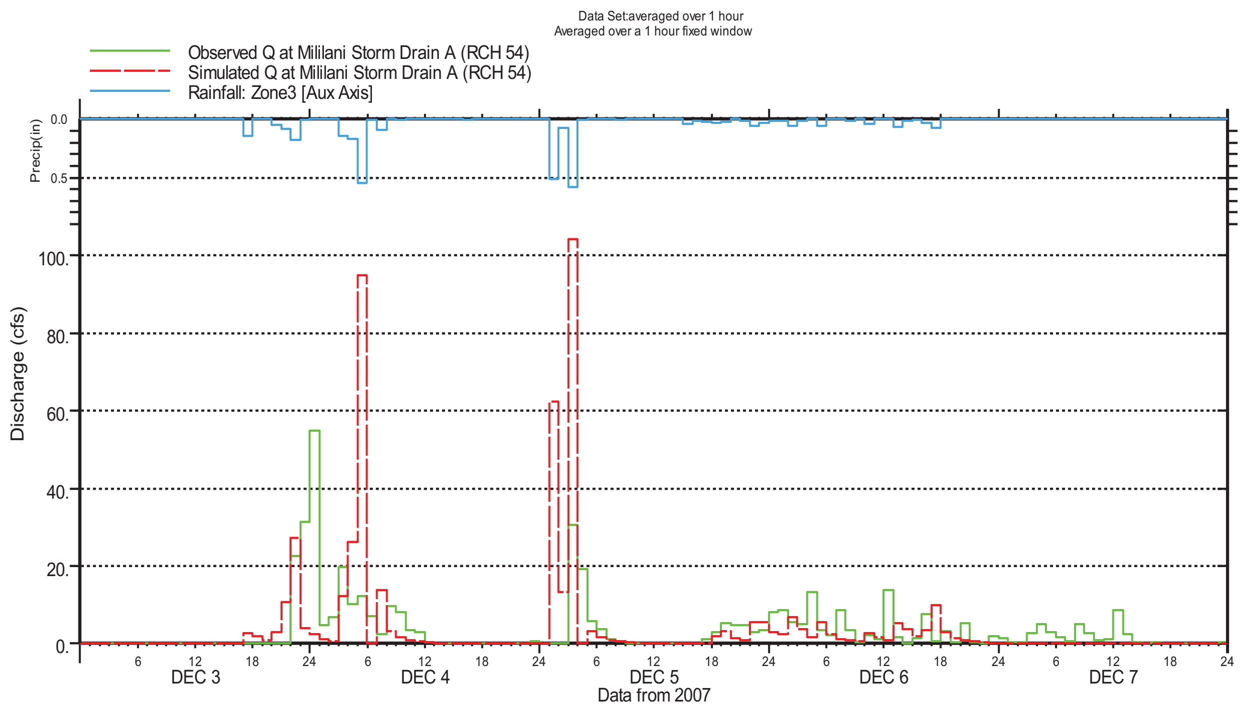


Figure B10: Hourly Stream Flow, Mililani Storm Drain A, December 5, 2007

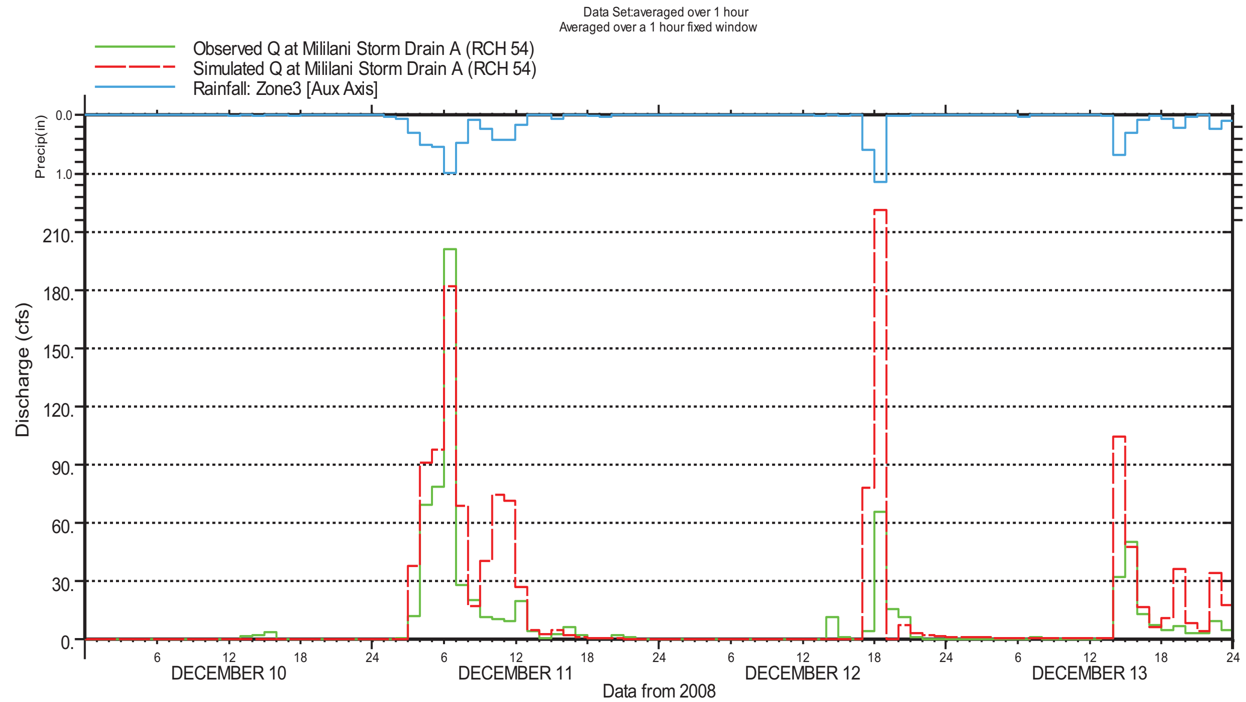


Figure B11: Hourly Stream Flow, Mililani Storm Drain A, December 11, 2008 Event

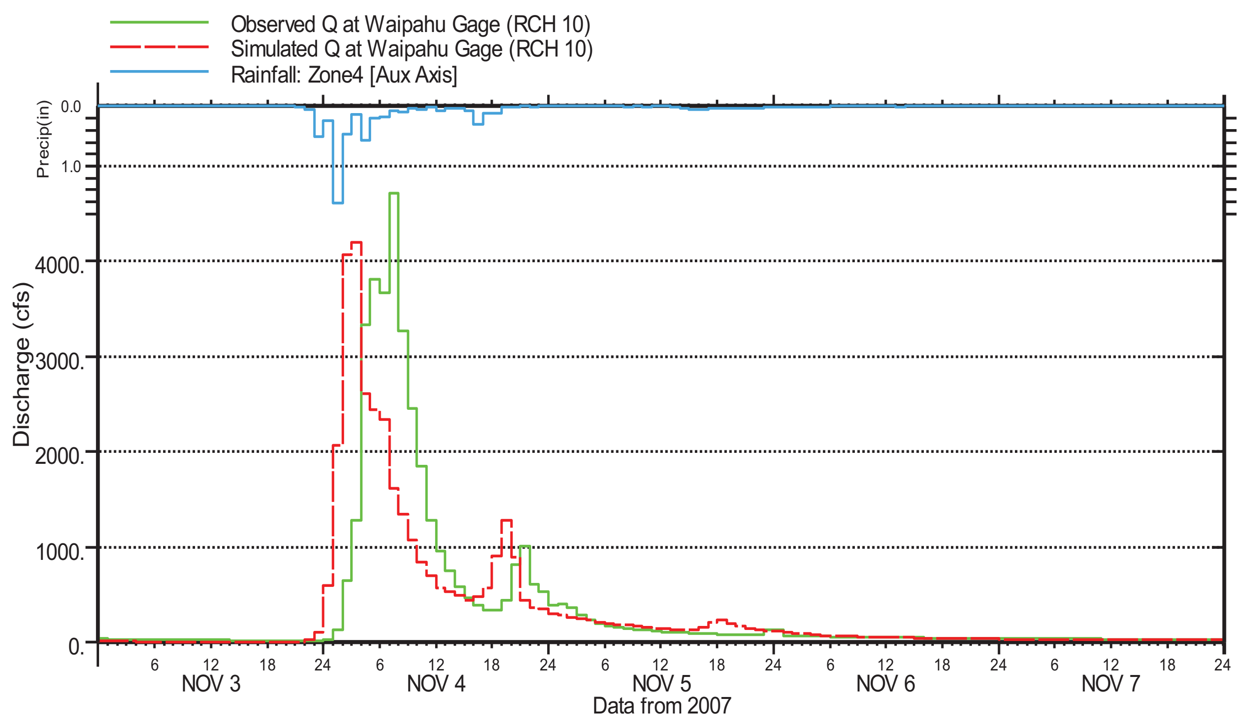


Figure B12: Hourly Stream Flow, Waikele Stream at Waipahu, November 4, 2007 Event

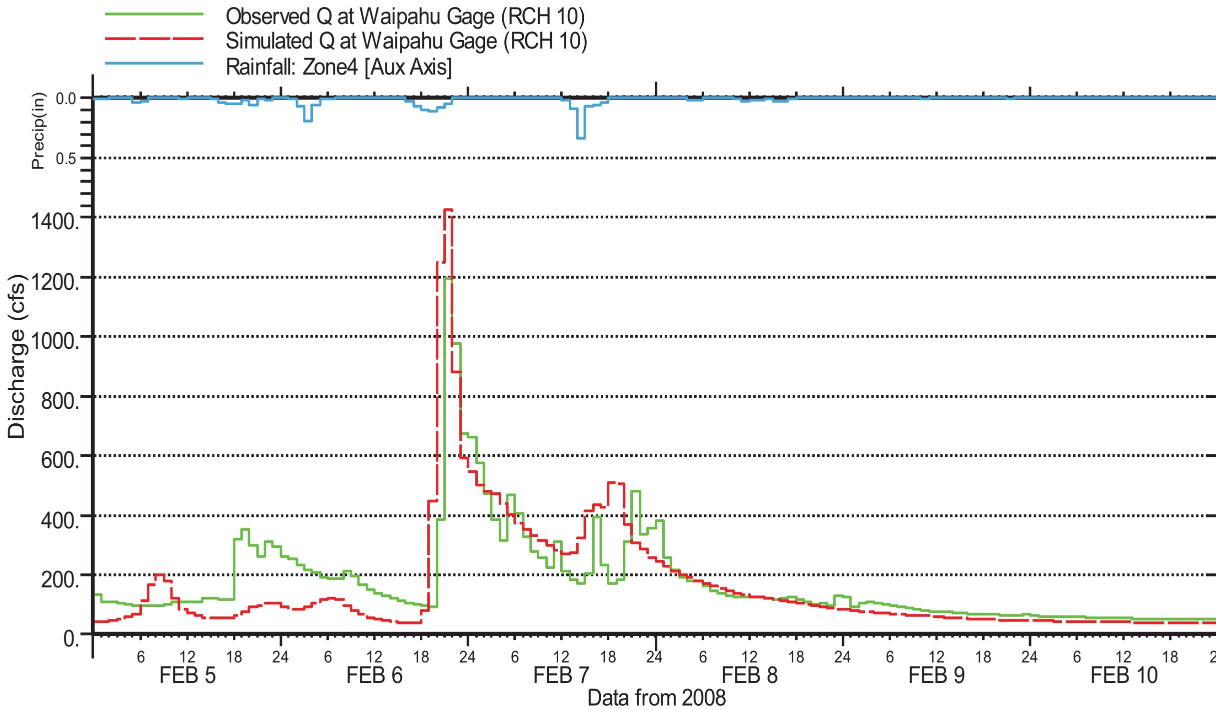


Figure B13: Hourly Stream Flow, Waikele Stream at Waipahu, February 7, 2008 Event

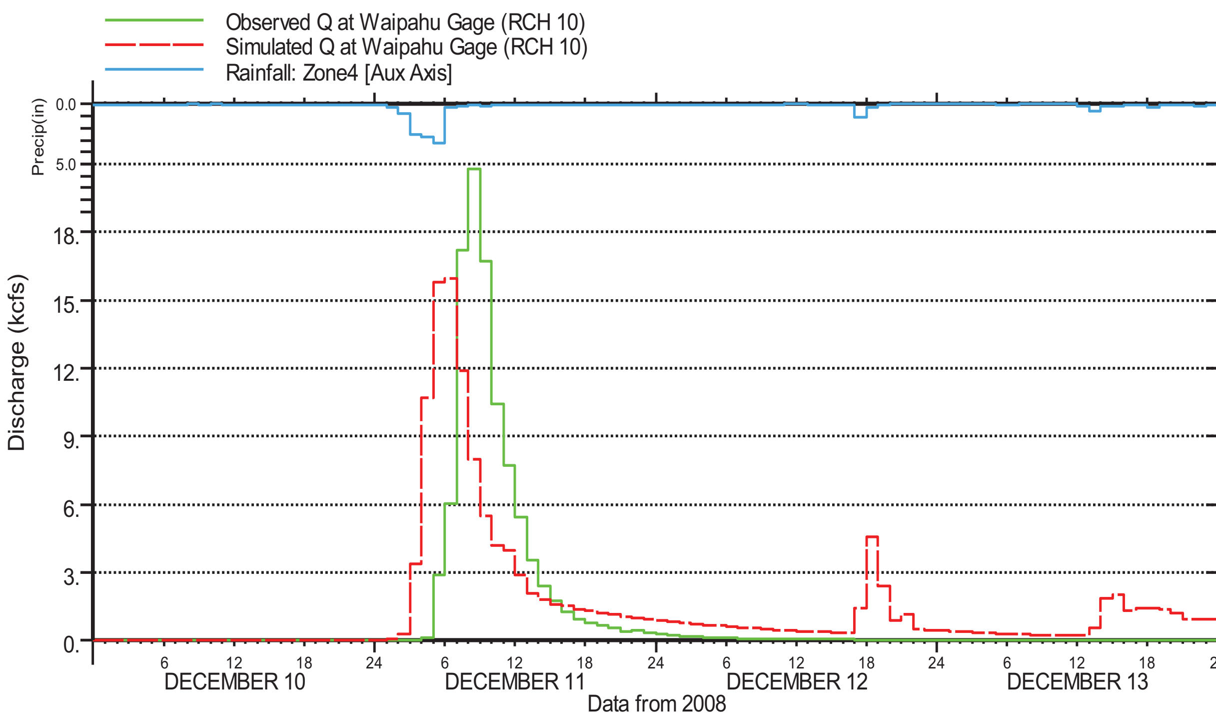


Figure B14: Hourly Stream Flow, Waikele Stream at Waipahu, December 11, 2008 Event

Appendix C: Daily Mean Flow Hydrographs and Sediment Pollutographs

APPENDIX C: Daily Mean Flow Hydrographs and Daily Sediment Load Pollutographs

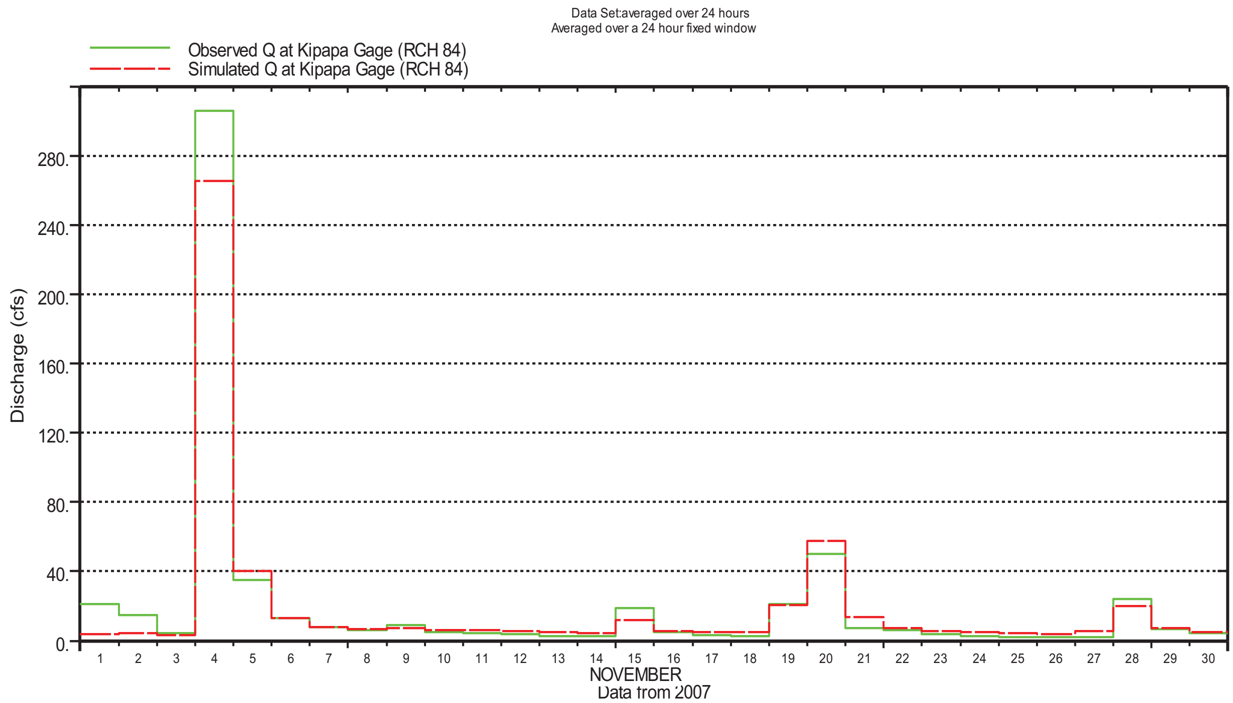


Figure C1A-Flow: Daily Stream Flow, Kipapa Stream near Wahiawa, November 4, 2007

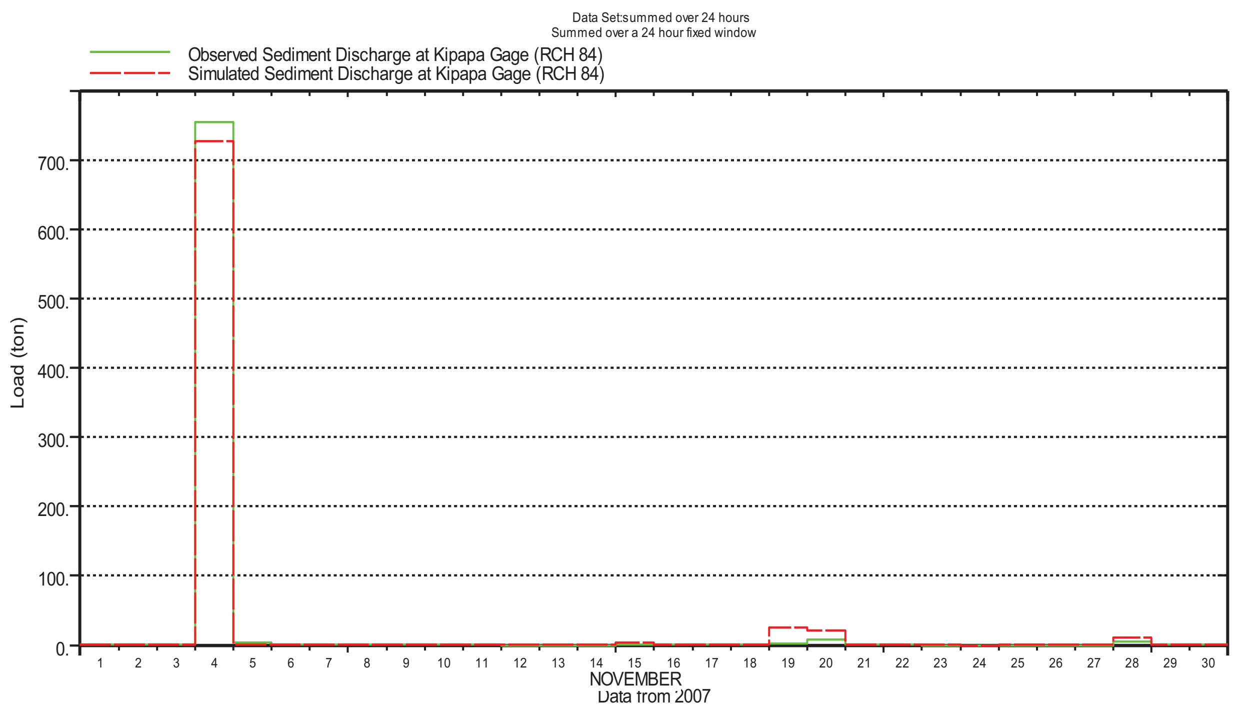


Figure C1B-Sediment: Daily Sediment Load, Kipapa Stream near Wahiawa, November, 2007

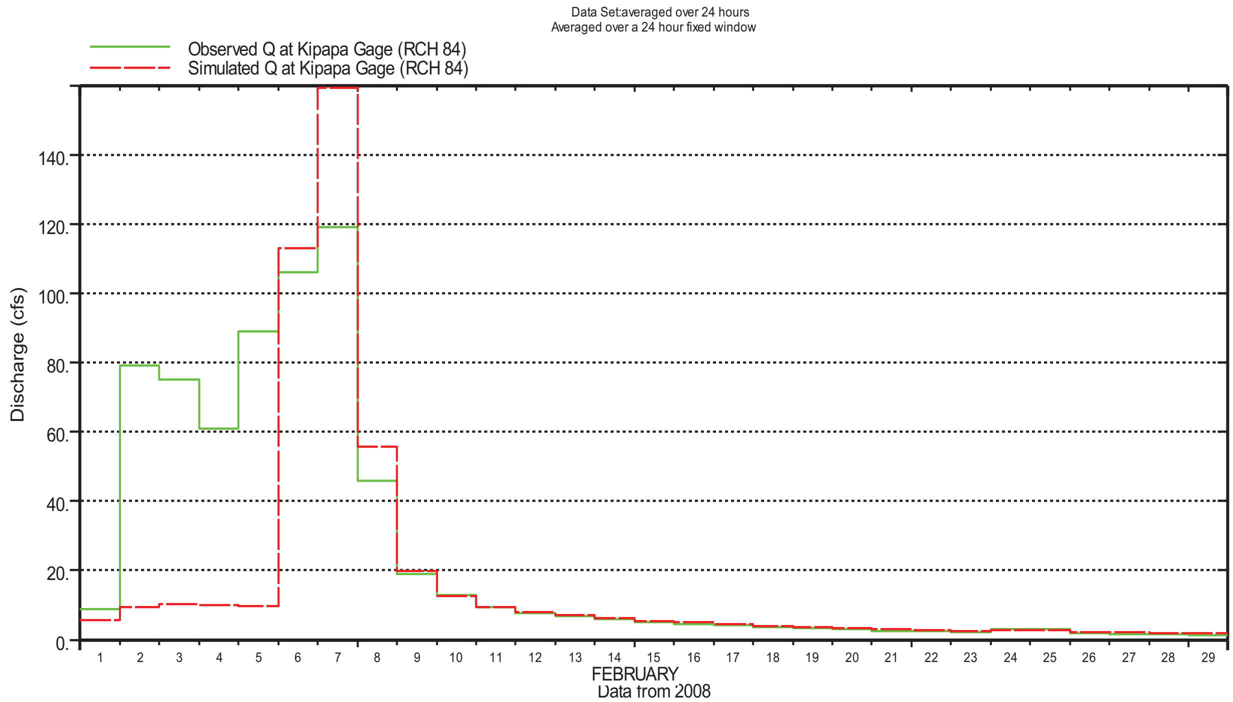


Figure C2A-Flow: Daily Stream Flow, Kipapa Stream near Wahiawa, February 7, 2008

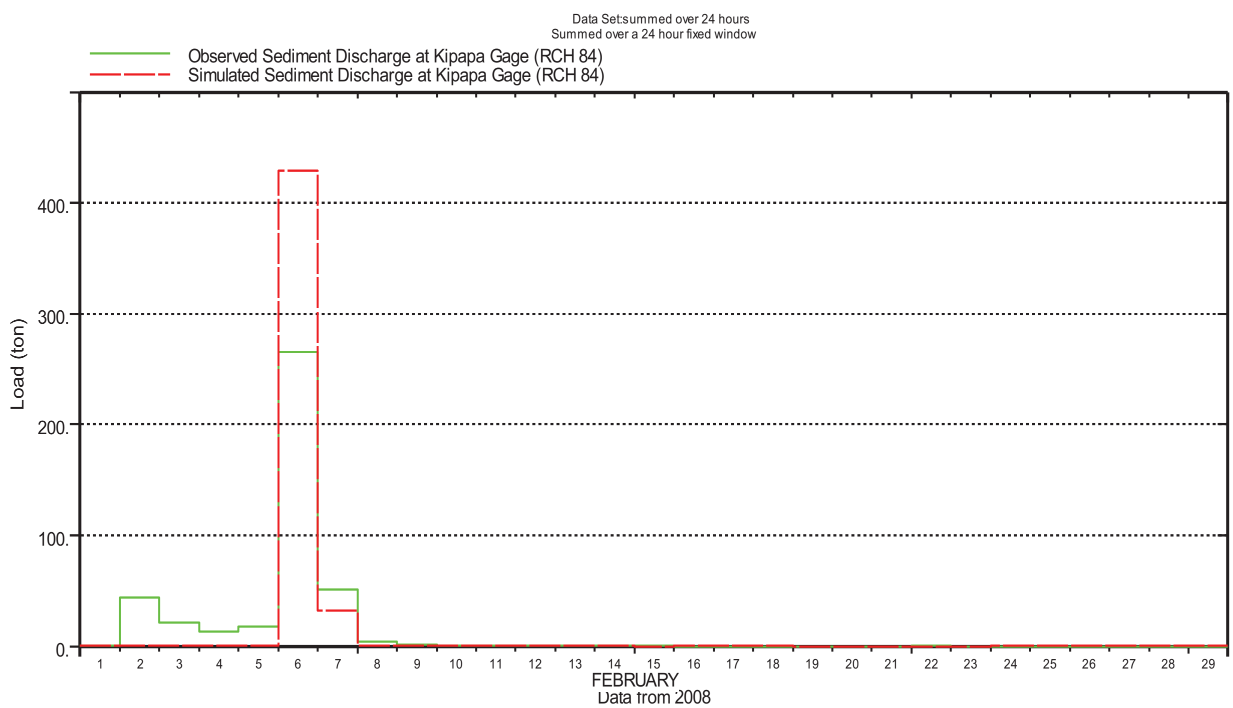


Figure C2B-Sediment: Daily Sediment Load, Kipapa Stream near Wahiawa, February, 2008

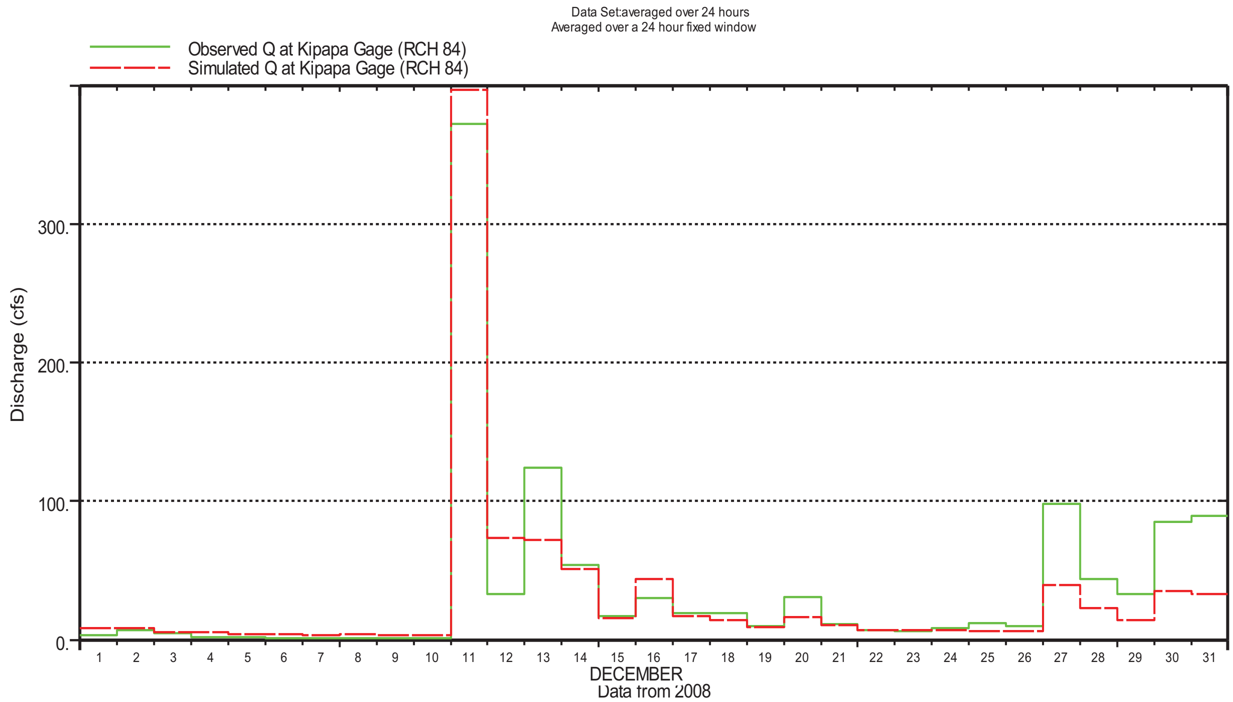


Figure C3A-Flow: Daily Stream Flow, Kipapa Stream near Wahiawa, December 11, 2008

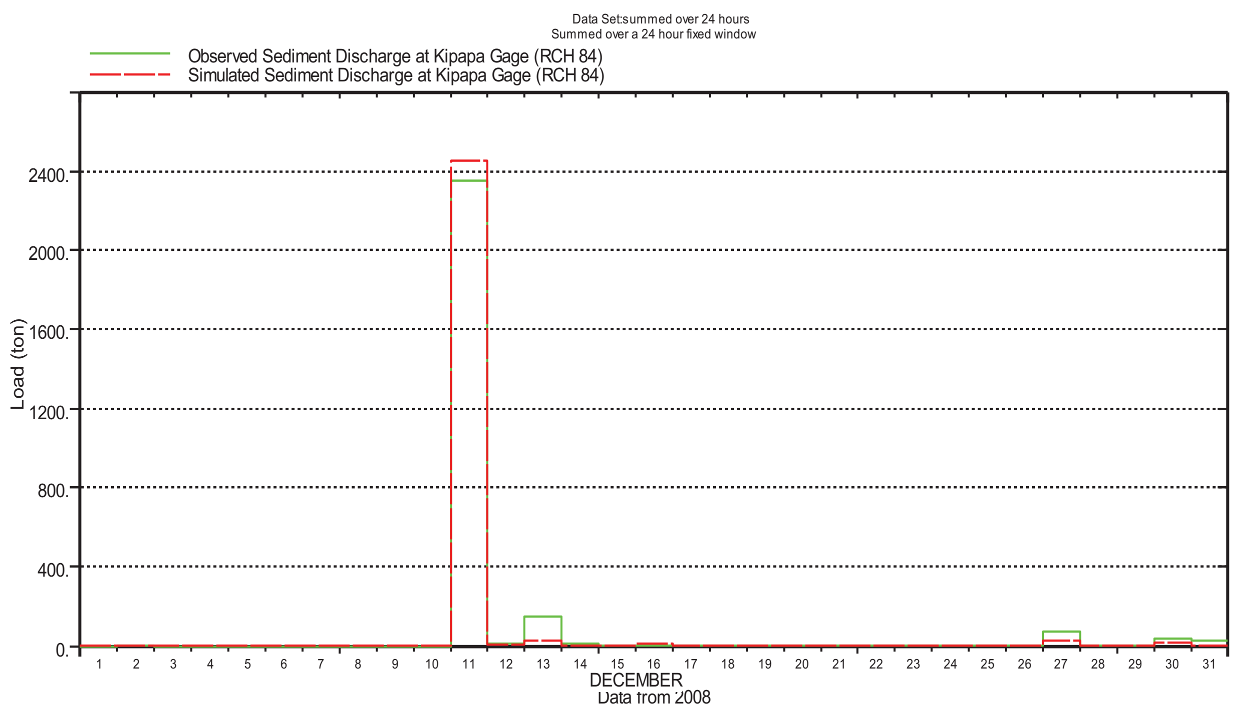


Figure C3B-Sediment: Daily Sediment Load, Kipapa Stream near Wahiawa, December, 2008

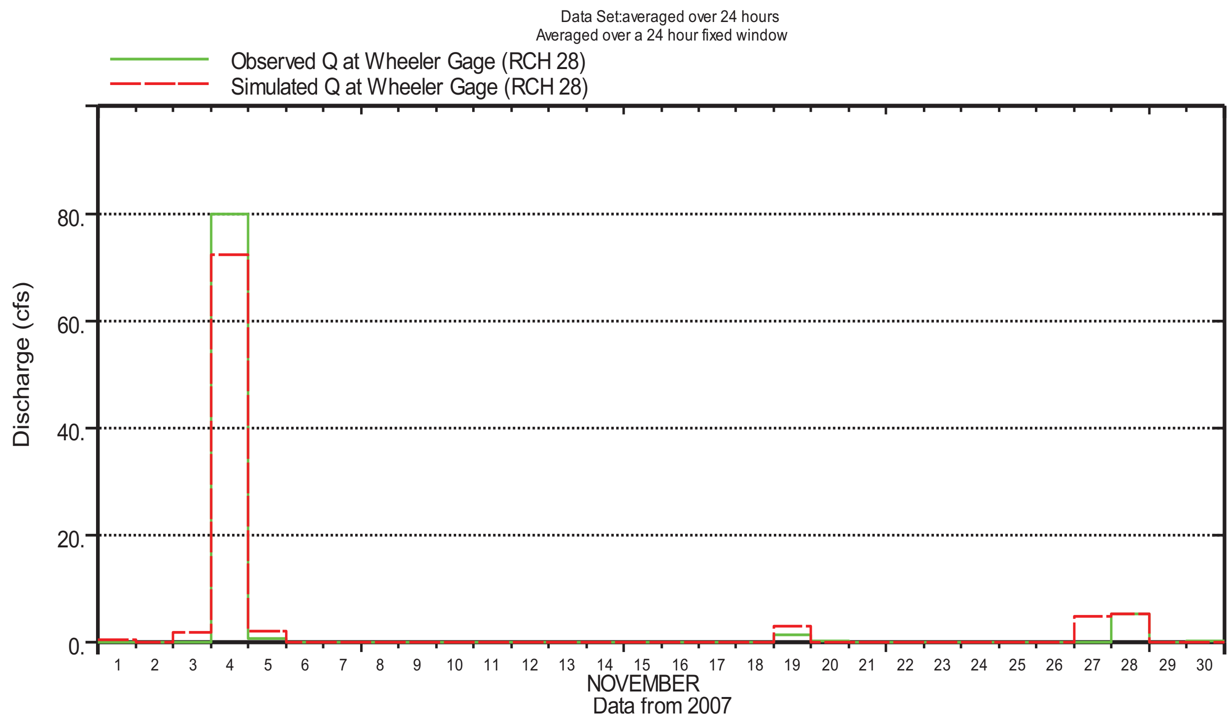


Figure C4A-Flow: Daily Stream Flow, Waikele Stream at Wheeler, November 4, 2007

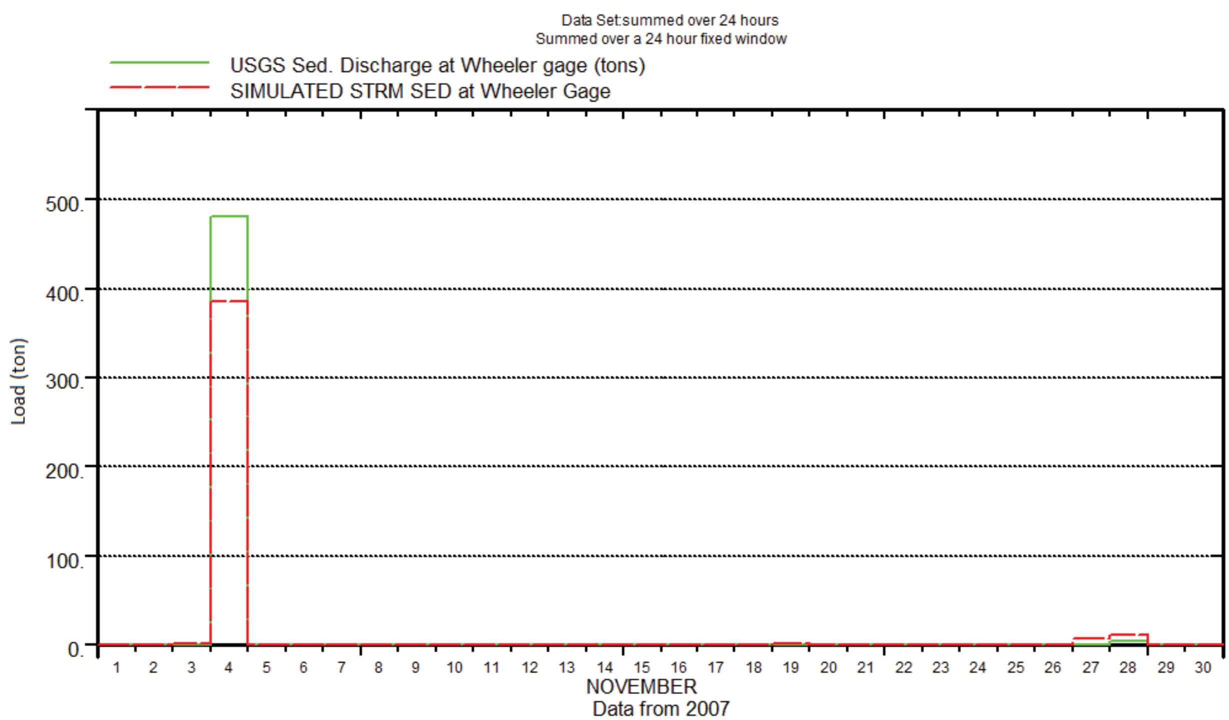


Figure C4B-Sediment: Daily Sediment Load, Waikele Stream at Wheeler, November, 2007

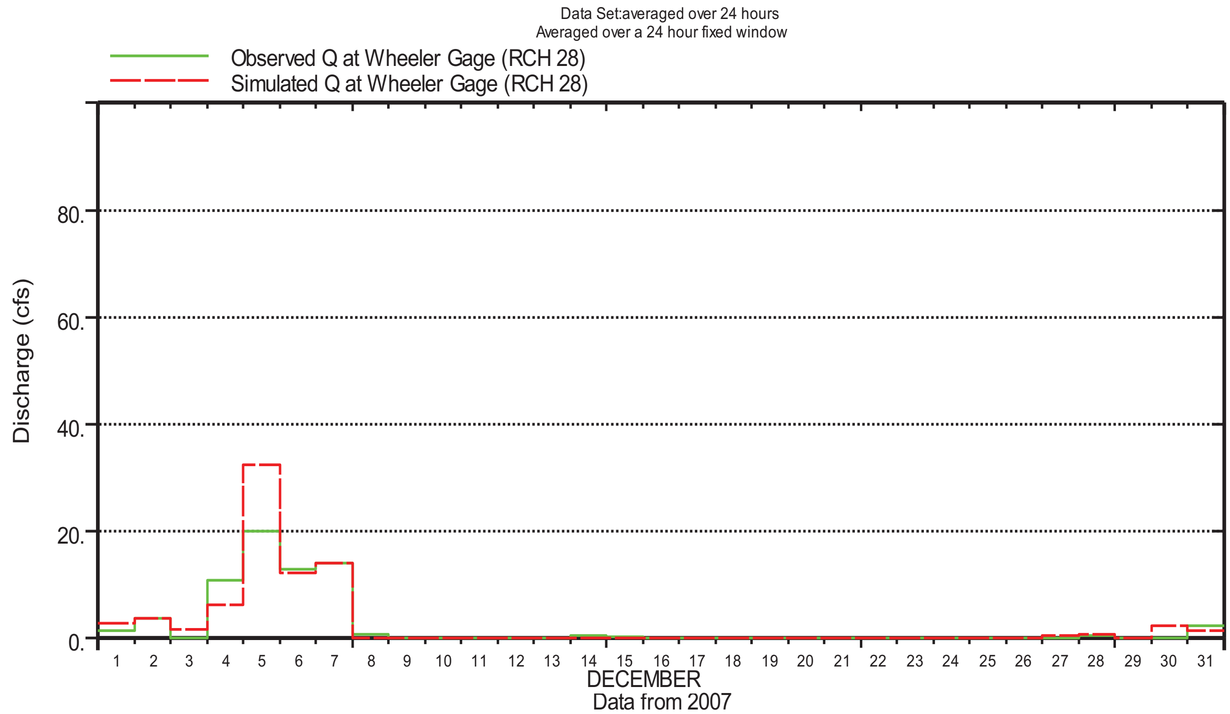


Figure C5A-Flow: Daily Stream Flow, Waikele Stream at Wheeler, December 5, 2007

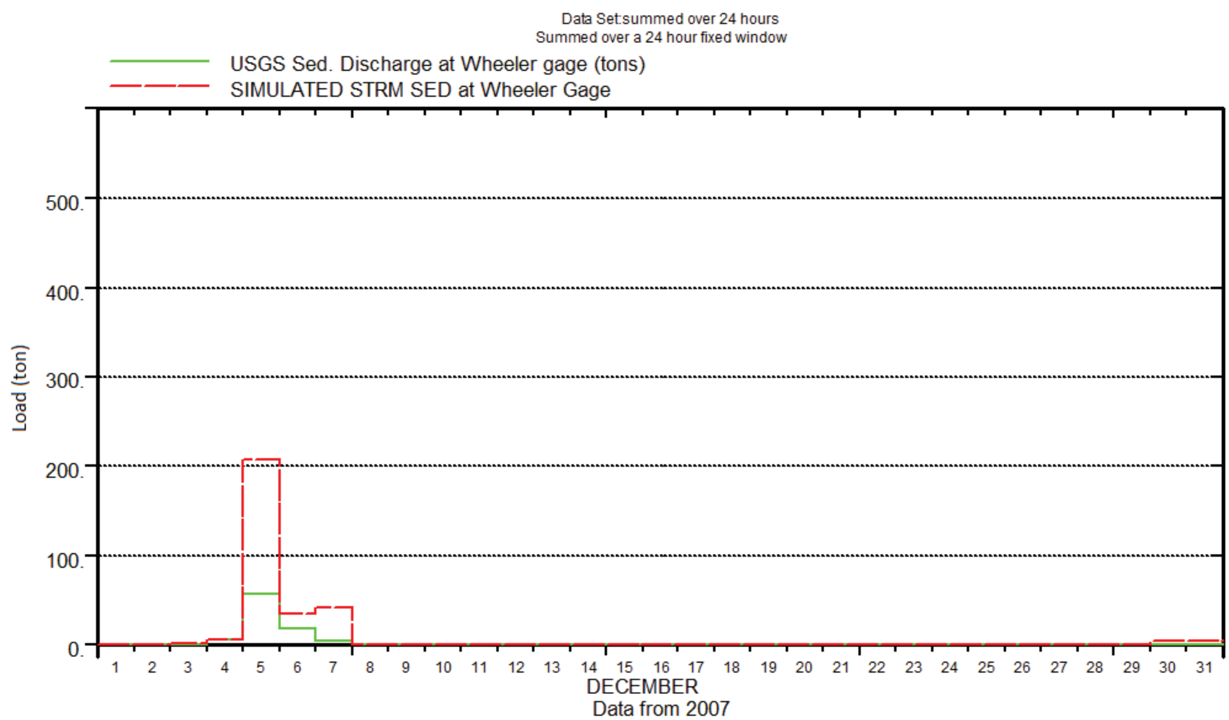


Figure C5B-Sediment: Daily Sediment Load, Waikele Stream at Wheeler, December, 2007

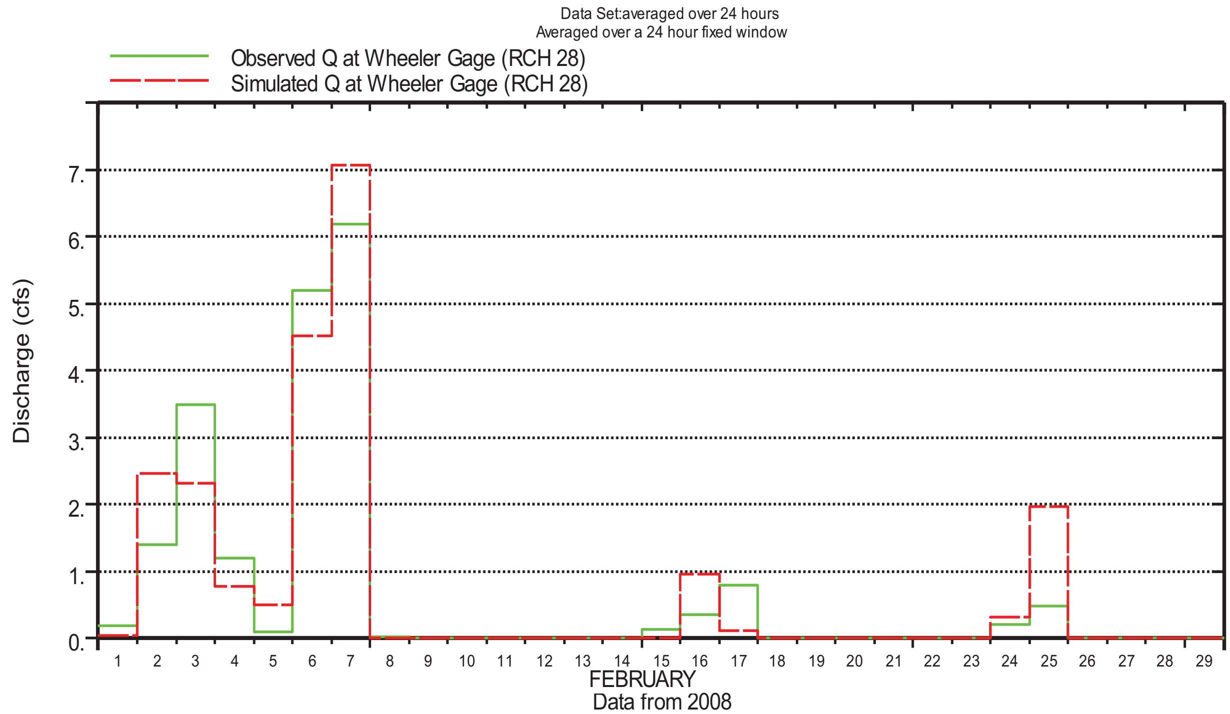


Figure C6A-Flow: Daily Stream Flow, Waikele Stream at Wheeler, February 7, 2008 Event

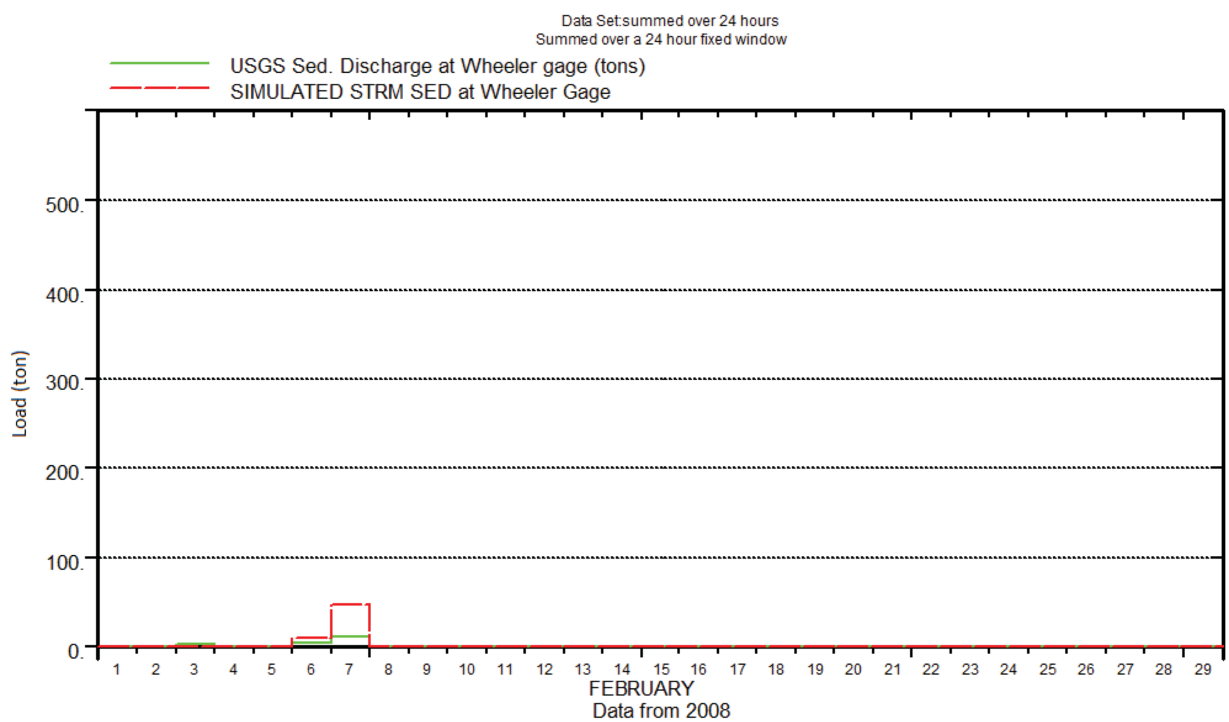


Figure C6B- Sediment: Daily Sediment Load, Waikele Stream at Wheeler, February, 2008 Event

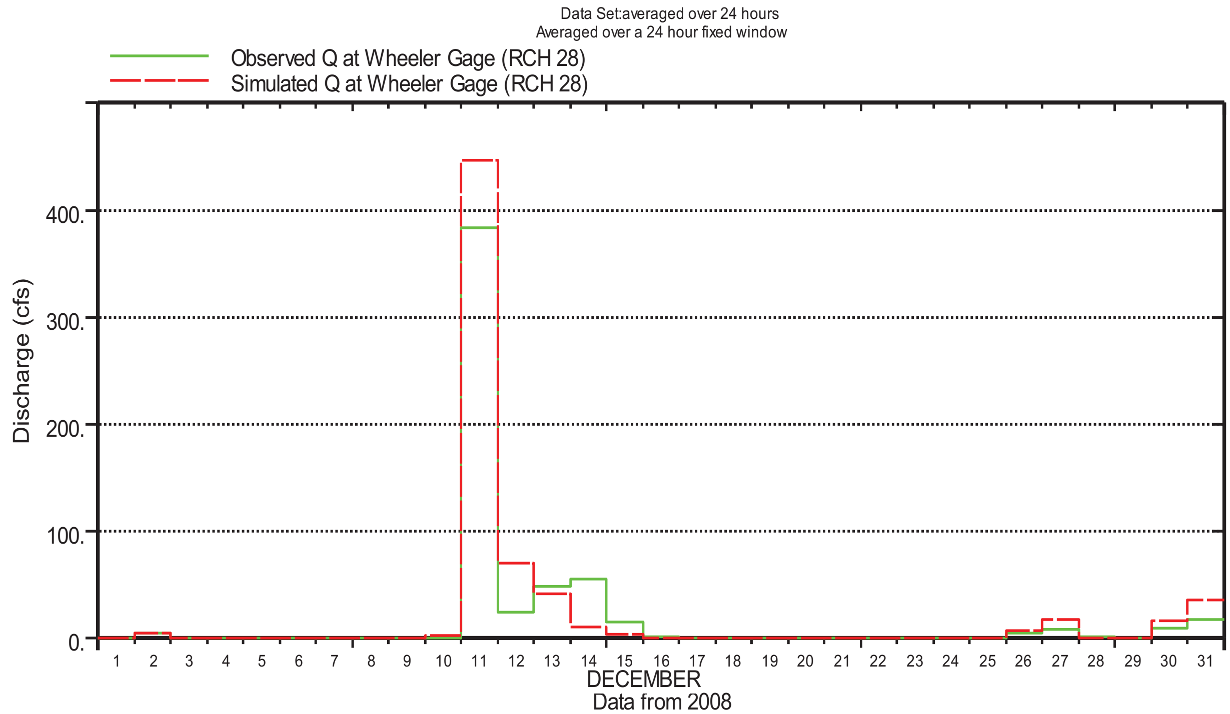


Figure C7A-Flow: Daily Stream Flow, Waikele Stream at Wheeler, December 11, 2008 Event

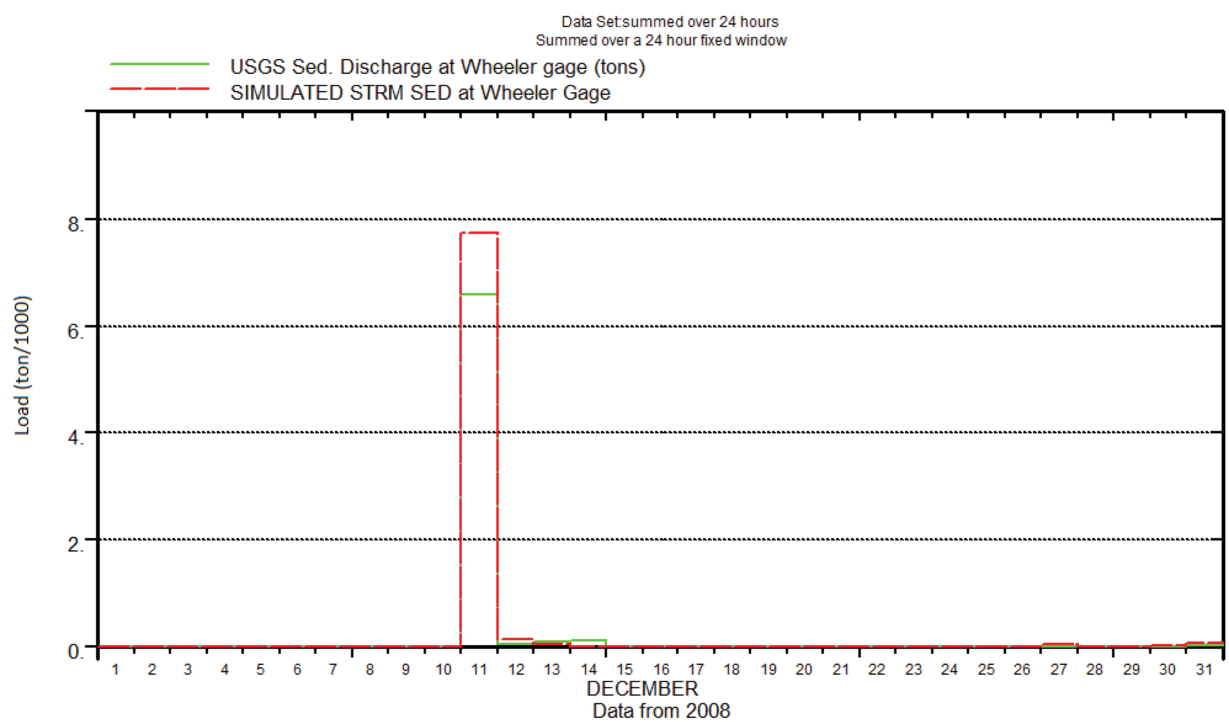


Figure C7B-Sediment: Daily Sediment Load, Waikele Stream at Wheeler, December, 2008 Event

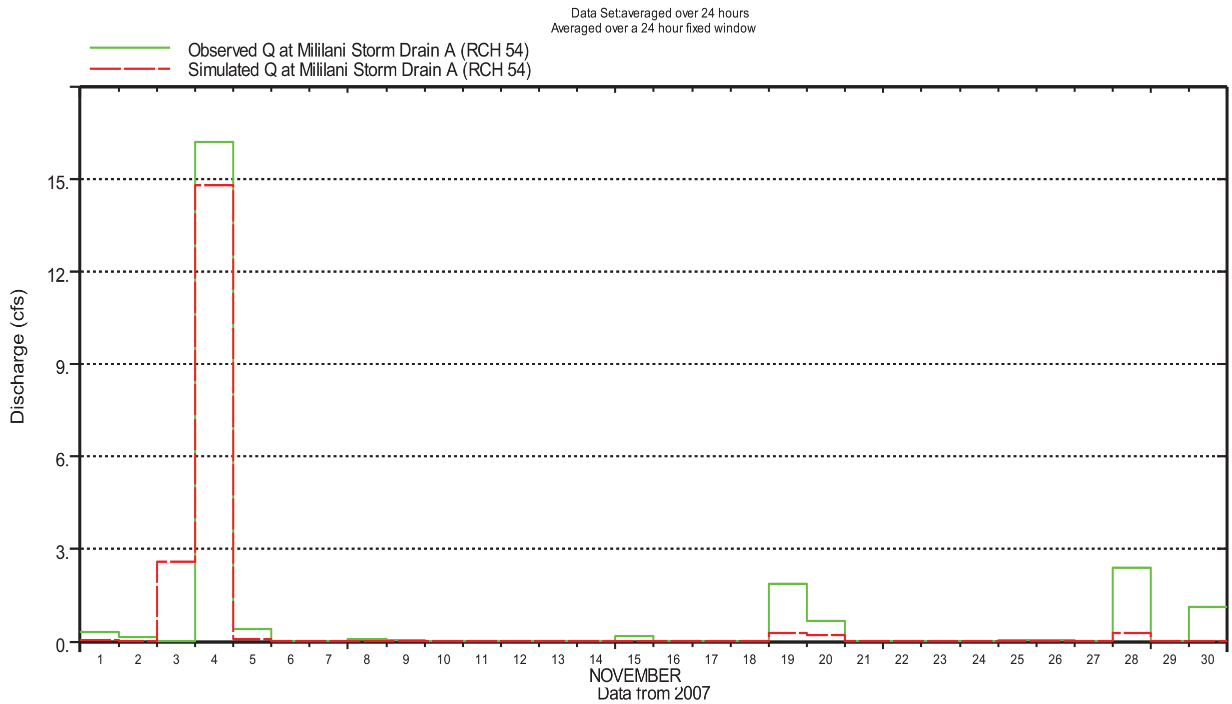


Figure C8A-Flow: Daily Stream Flow, Mililani Storm Drain A, November 4, 2007

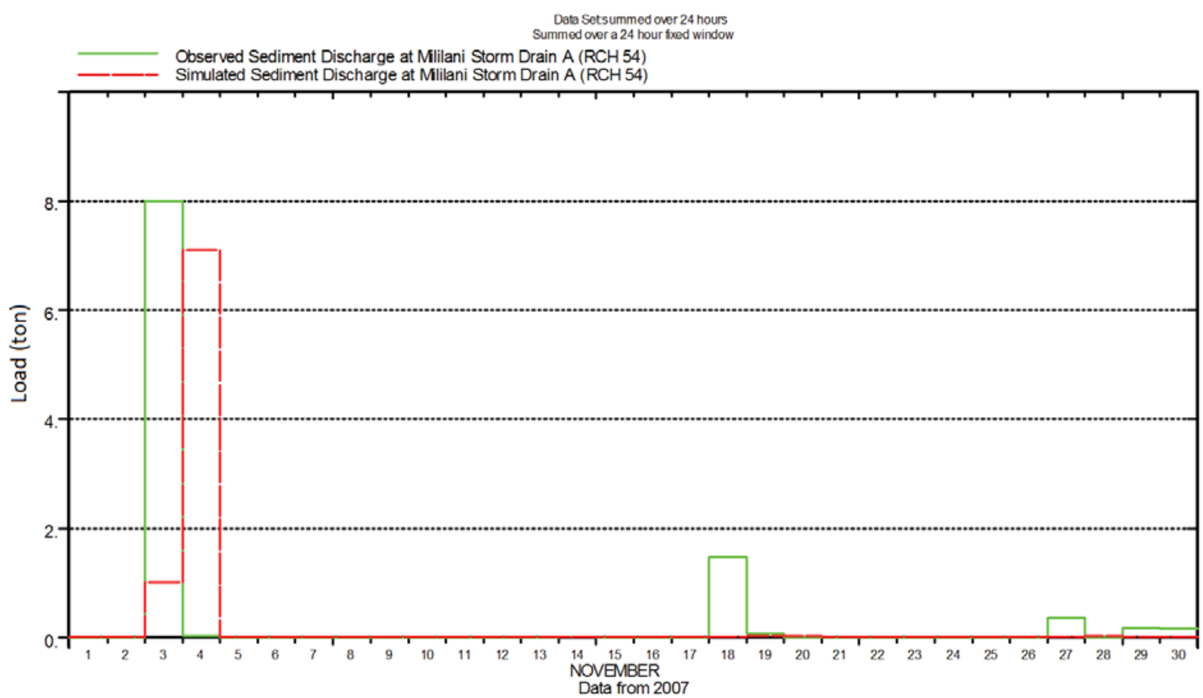


Figure C8B-Sediment: Daily Sediment Load, Mililani Storm Drain A, November, 2007

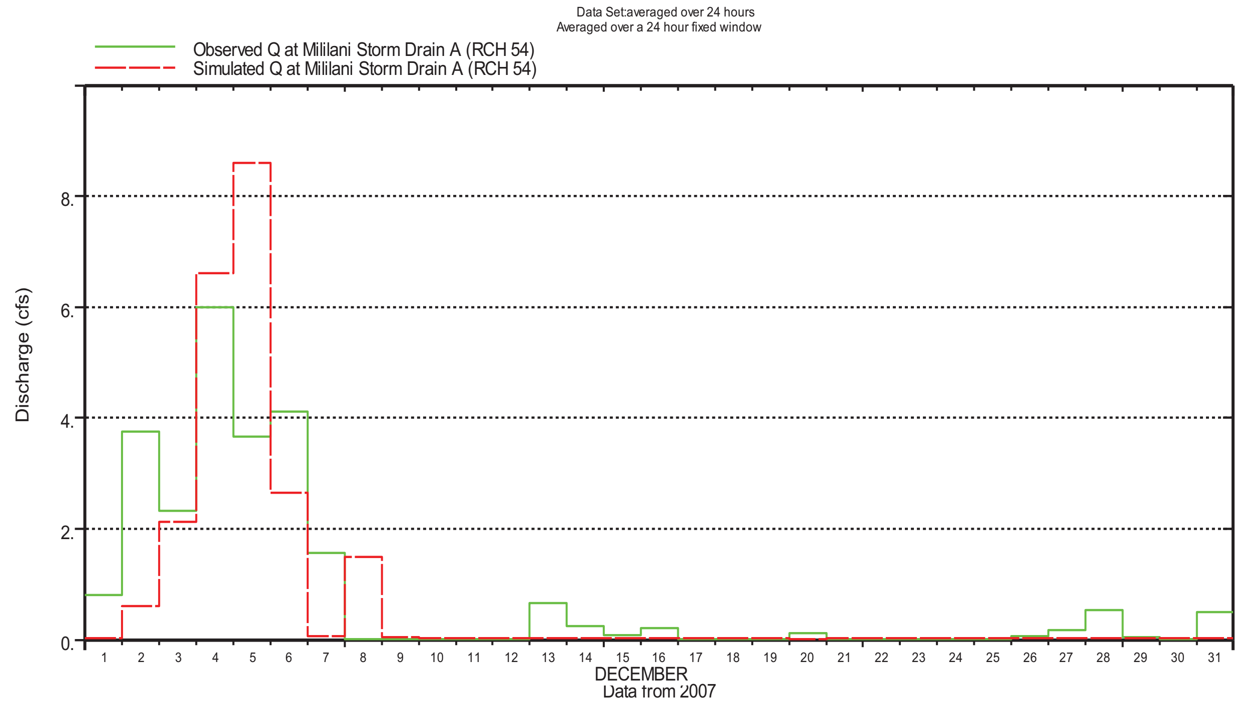


Figure C9A-Flow: Daily Stream Flow, Mililani Storm Drain A, December 5, 2007

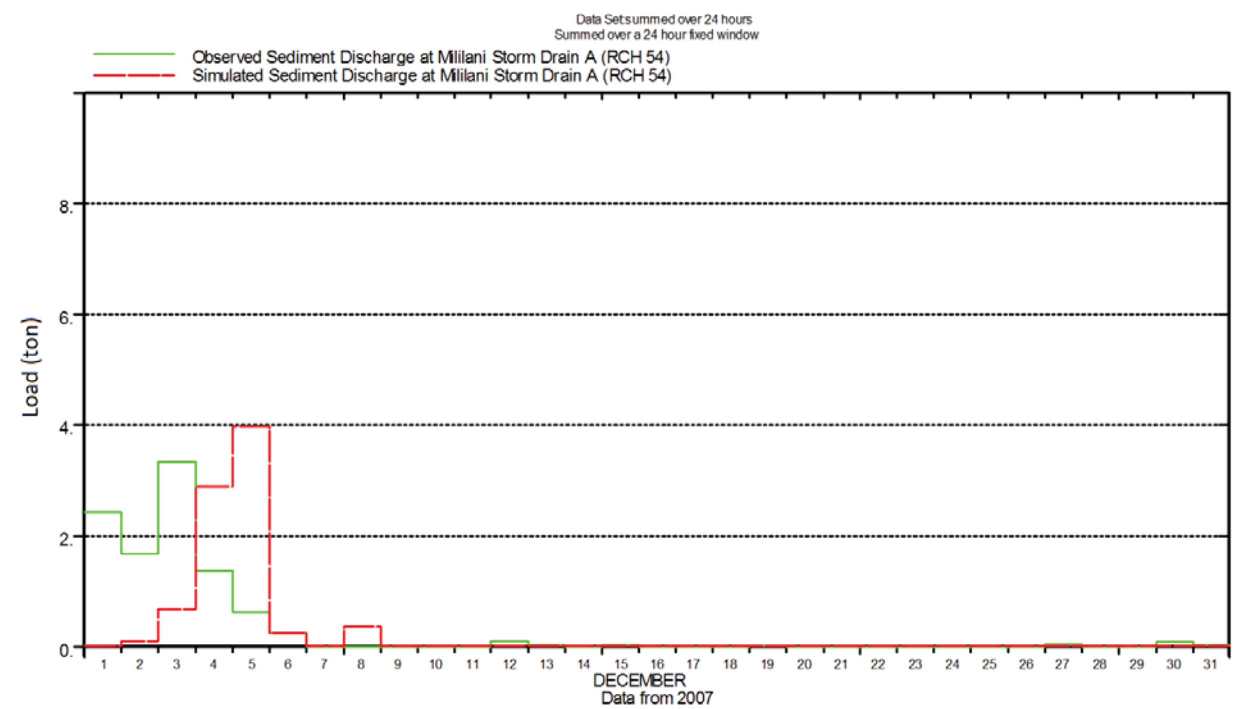


Figure C9B-Sediment: Daily Sediment Load, Mililani Storm Drain A, December, 2007

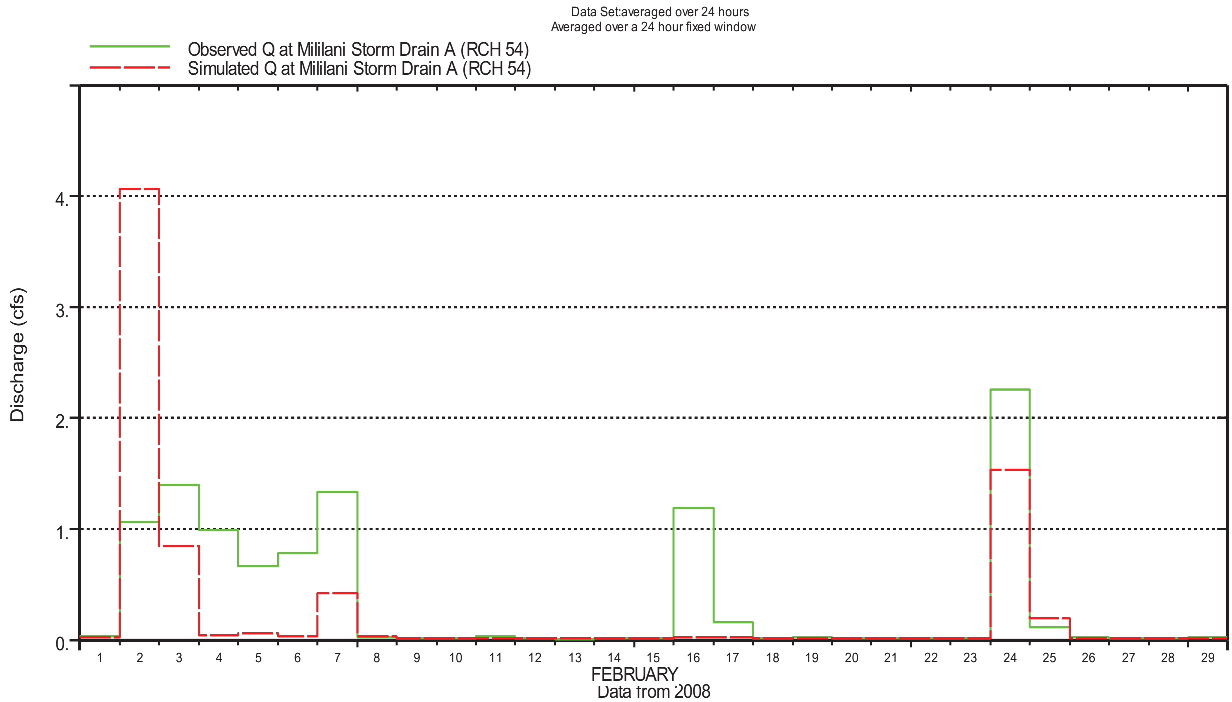


Figure C10A-Flow: Daily Stream Flow, Mililani Storm Drain A, February 7, 2008 Event

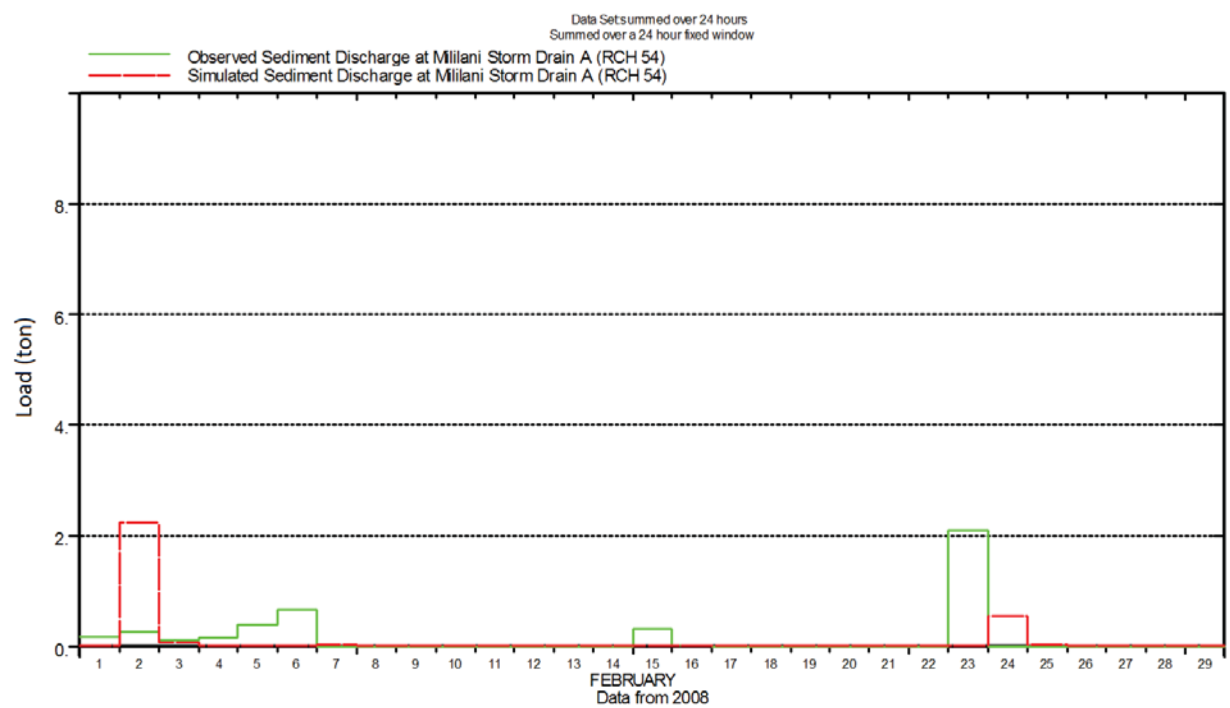


Figure C10B- Sediment: Daily Sediment Load, Mililani Storm Drain A, February, 2008 Event

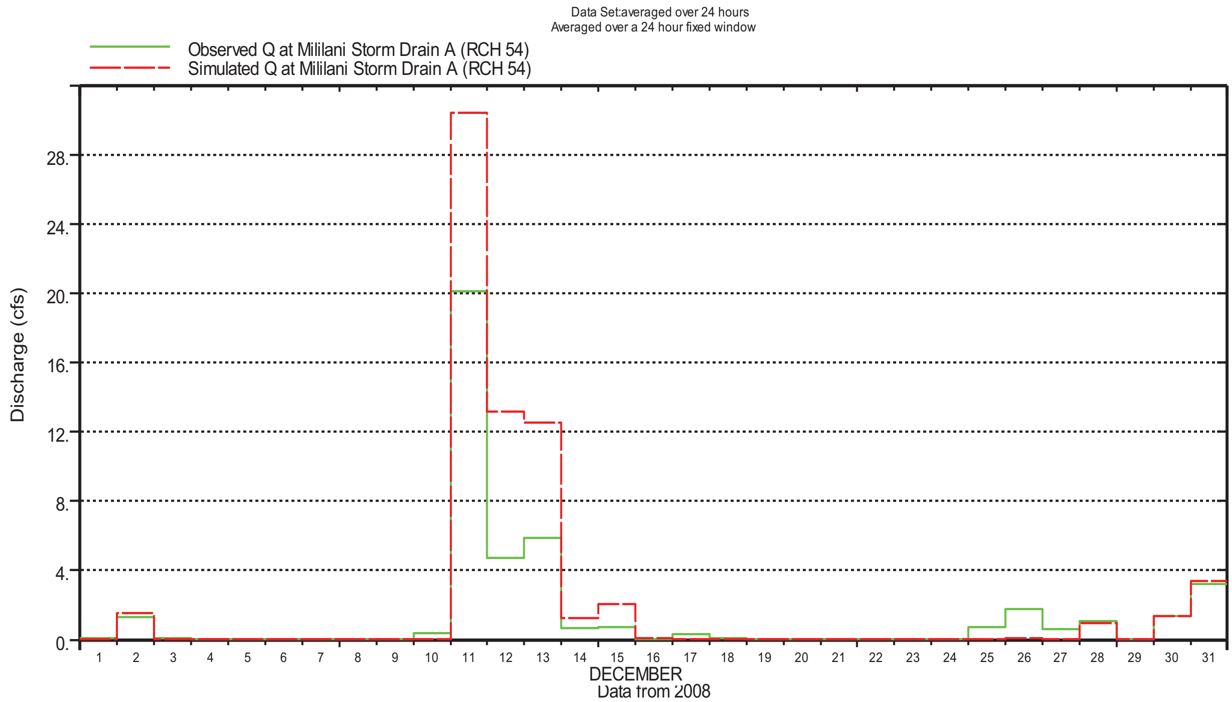


Figure C11A-Flow: Daily Stream Flow, Mililani Storm Drain A, December 11, 2008 Event

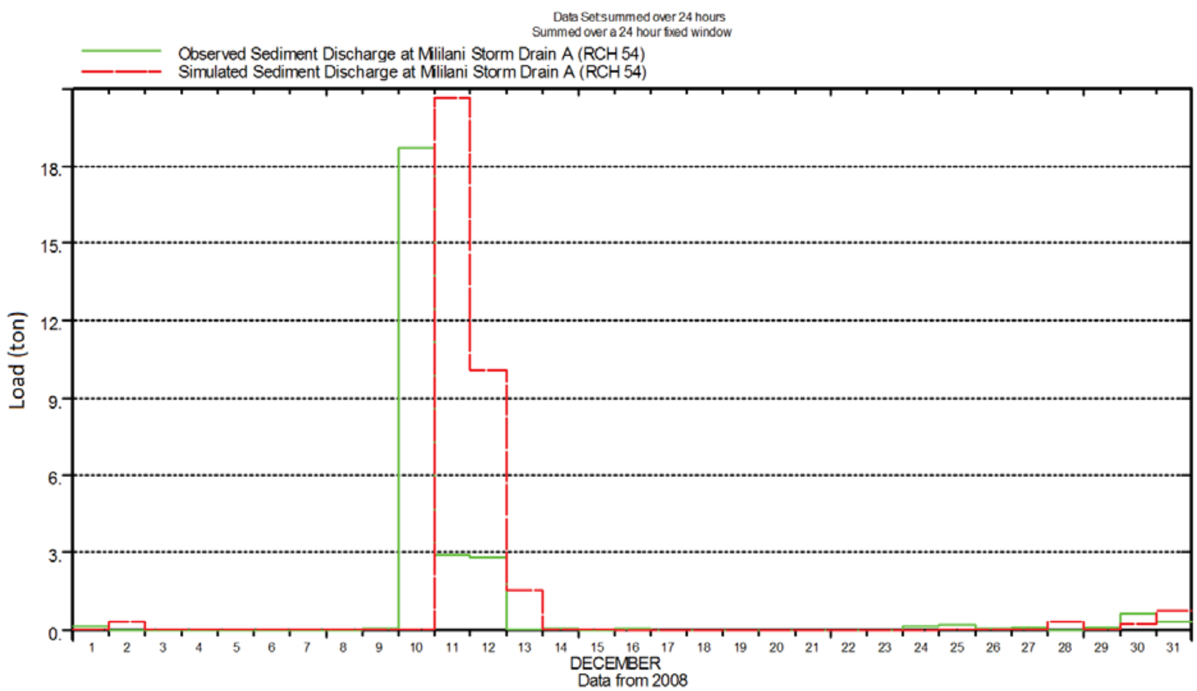


Figure C11B-Sediment: Daily Sediment Load, Mililani Storm Drain A, December, 2008 Event

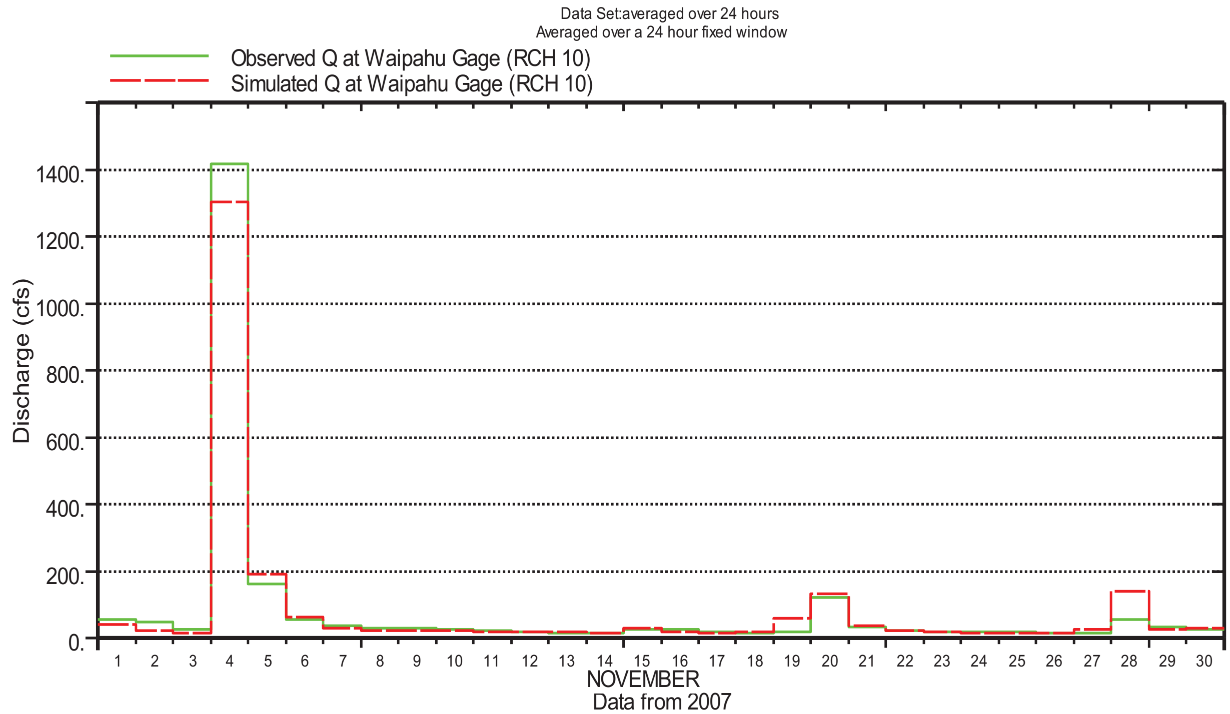


Figure C12A-Flow: Daily Stream Flow, Waikele Stream at Waipahu, November 4, 2007 Event

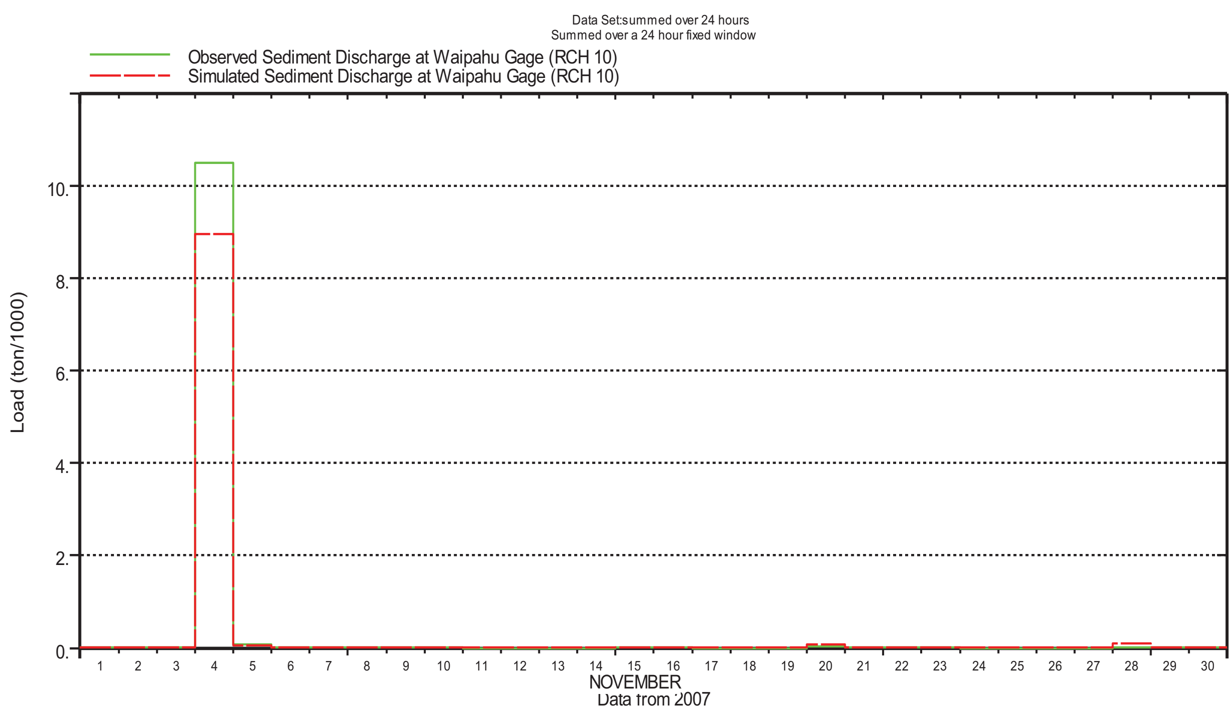


Figure C12B-Sediment: Daily Sediment Load, Waikele Stream at Waipahu, November, 2007 Event

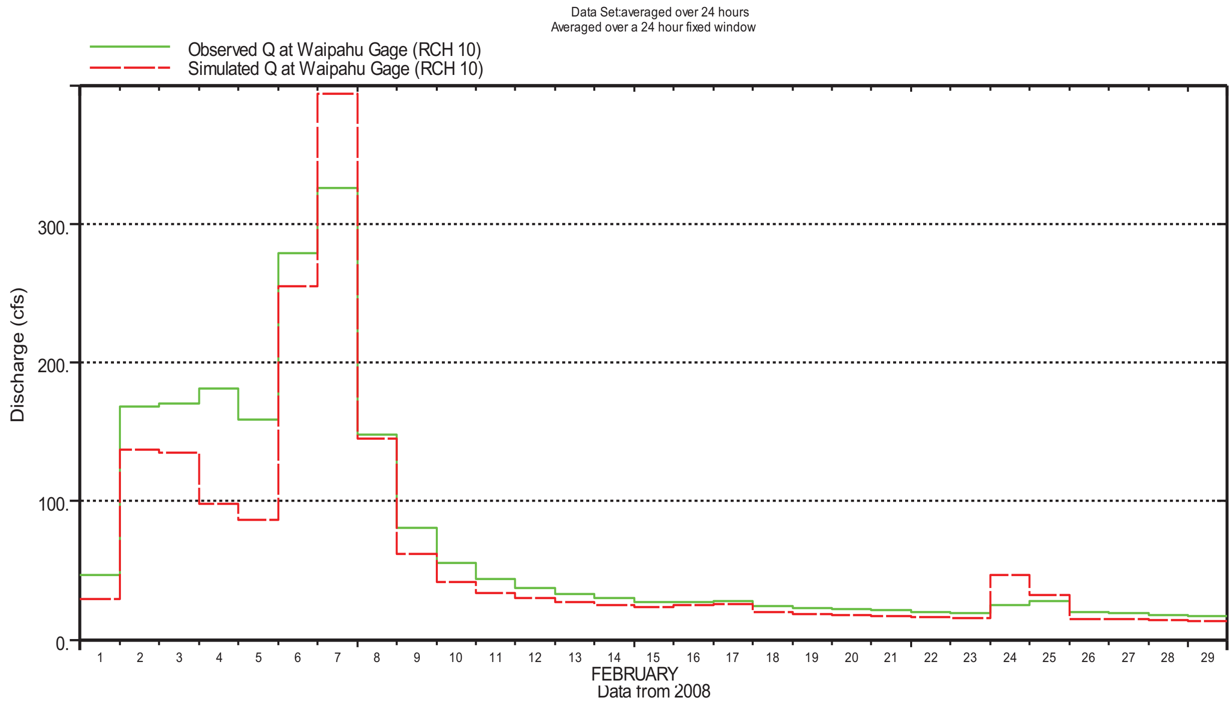


Figure C13A-Flow: Daily Stream Flow, Waikele Stream at Waipahu, February 7, 2008 Event

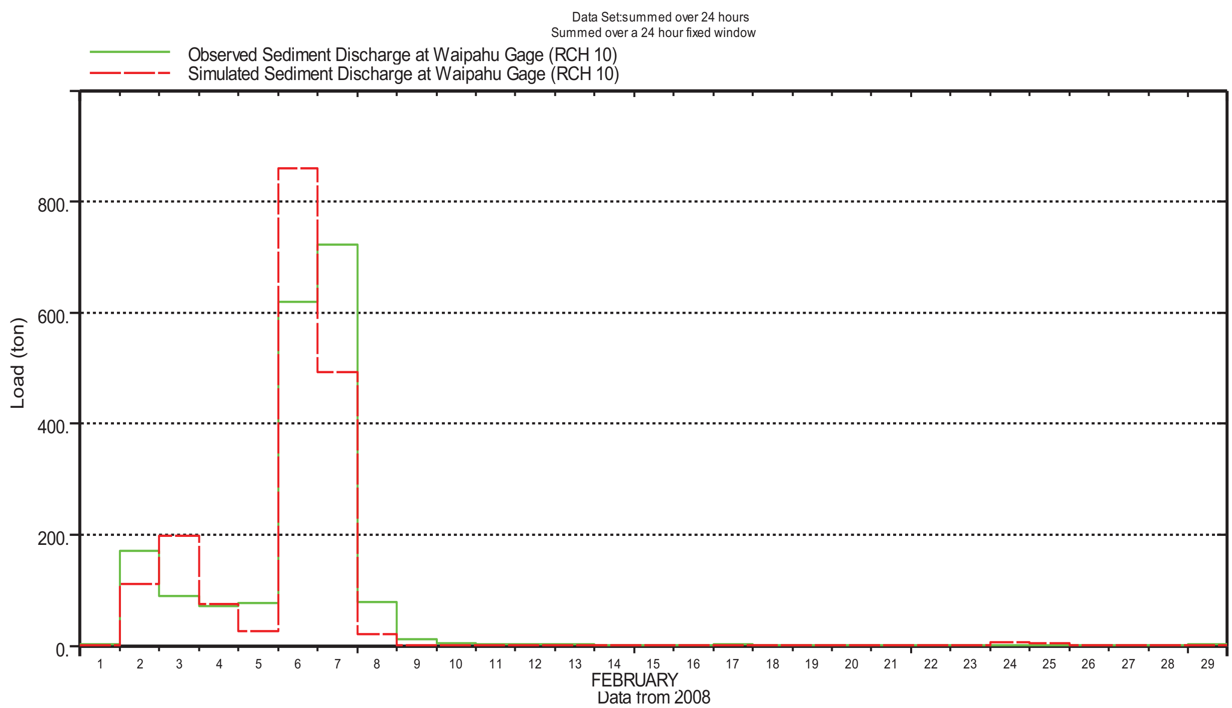


Figure C13B-Sediment: Daily Sediment Load, Waikele Stream at Waipahu, February, 2008 Event

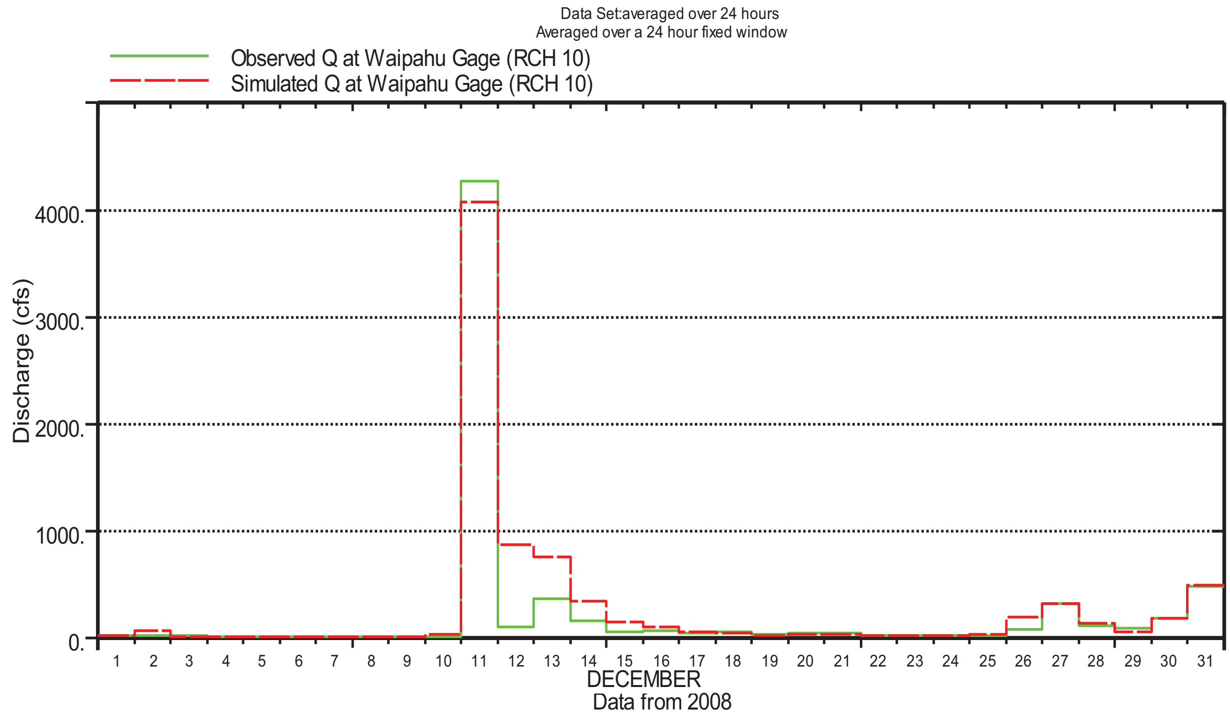


Figure C14A-Flow: Daily Stream Flow, Waikele Stream at Waipahu, December 11, 2008 Event

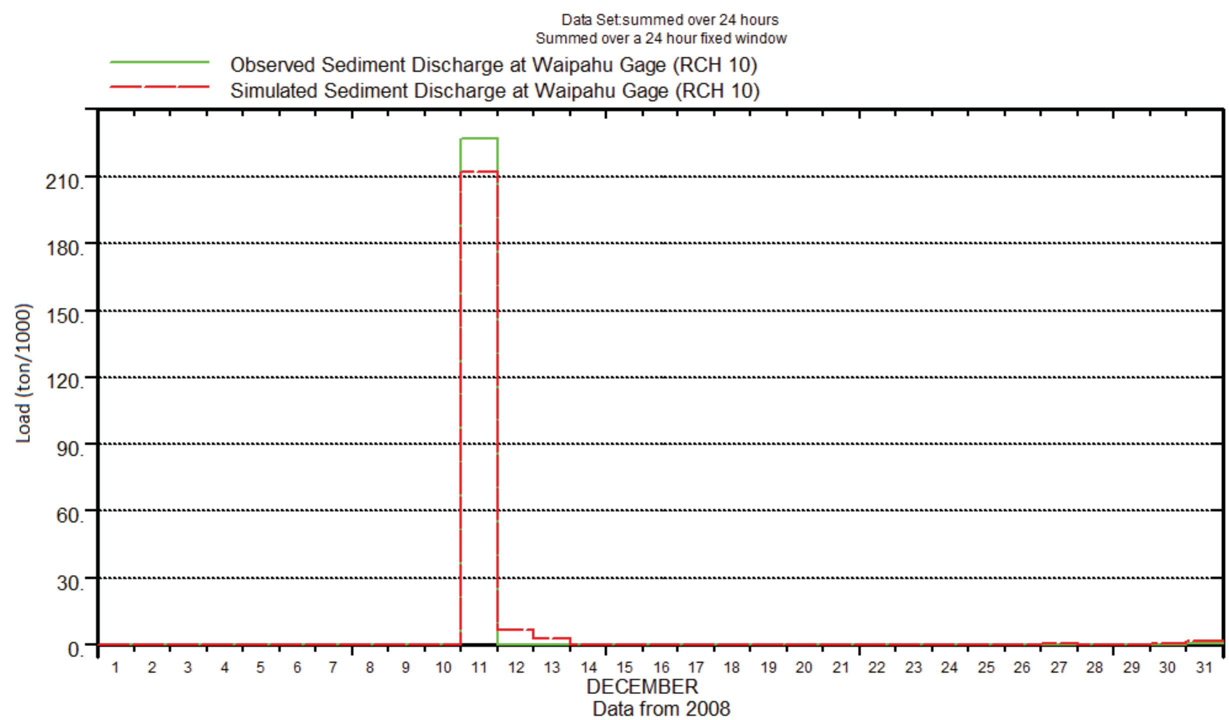


Figure C14B-Sediment: Daily Sediment Load, Waikele Stream at Waipahu, December, 2008 Event