COST-EFFECTIVENESS OF THE STREAM-GAGING PROGRAM IN THE HAWAII DISTRICT

By I. Matsuoka, R. Lee, and W. O. Thomas, Jr.

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Multiply inch-pound units	By	To obtain SI units
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

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ABSTRACT

This report documents the results of a study of the cost-effectiveness of the stream-gaging program in the Hawaii District. The stream gages in the District were divided into two groups, the State of Hawaii and the Other Pacific Areas. Data uses and funding sources were identified for the 124 continuous stream gages currently being operated in the Hawaii District with a budget of $570,620. All the stream gages were identified as having sufficient reason to continue their operation and they should be maintained in the program for the foreseeable future.

The current policy for operation of the 92-station program for the State of Hawaii part of the District program requires a budget of $413,370 per year. The average standard error of estimate of streamflow records is 21.0 percent. It was shown that this overall level of accuracy could be improved to 17.7 percent with the same budget if the gaging resources were redistributed among the gages. A minimum budget of $370,000 is required to operate the 92-gage program; a budget less than this does not permit proper service and maintenance of the gages and recorders. At the minimum budget, the average standard error is 23.7 percent. The maximum budget analyzed was $550,000, which resulted in an average standard error of 12.9 percent. Some parts of Hawaii were identified as having very few or no current streamflow stations. This is a reflection of discontinuing gaging stations in the past. There are no immediate suggestions for discontinuing or establishing gages on the basis of this study.

The current policy for operation of the 32-station program for the Other Pacific Areas part of the District program requires a budget of $157,250 per year. The average standard error of estimation of streamflow records is 25.9

percent. It was shown that this overall level of accuracy could be improved to 23.2 percent with the same budget if the gaging resources were redistributed among the gages. A minimum budget of $145,000 is required to operate the 32-gage program; a budget less than this does not permit proper service and maintenance of the gages and recorders. At the minimum budget, the average standard error is 32.0 percent. The maximum budget analyzed was $250,000, which resulted in an average standard error of 12.2 percent. There are no immediate suggestions for discontinuing or establishing new gaging stations in the Other Pacific Areas at this time.

INTRODUCTION

The U.S. Geological Survey (USGS) is the principal Federal agency collecting surface-water data in the Nation. The collection of these data is a major activity of the Water Resources Division of the USGS. The data are collected in cooperation with State and local governments and other Federal agencies. The USGS is presently (1983) operating approximately 8,000 continuous-record gaging stations throughout the Nation. Some of these records extend back to the turn of the century. Any activity of long standing, such as the collection of surface-water data, should be reexamined at intervals, if not continuously, because of changes in objectives, technology, or external constraints. The last systematic nationwide evaluation of the streamflow information program was completed in 1970 and is documented by Benson and Carter (1973). The USGS is presently (1983) undertaking another nationwide analysis of the stream-gaging program that will be completed over a 5-year period with 20 percent of the program being analyzed each year. The objective of this analysis is to define and document the most cost-effective means of furnishing streamflow information.

For every continuous-record gaging station, the analysis identifies the principal uses of the data and relates these uses to funding sources. Gaged sites for which data are no longer needed are identified, as are deficient or unmet data demands. In addition, gaging stations are categorized as to whether the data are available to users in a real-time sense, on a provisional basis, or at the end of the water year.

The second aspect of the analysis is to identify less costly alternate methods of furnishing the needed information; among these are flow-routing models and statistical methods. The stream-gaging activity no longer is considered a network of observation points, but rather an integrated information system in which data are provided both by observation and synthesis.

The final part of the analysis involves the use of Kalman-filtering and mathematical-programming techniques to define strategies for operation of the necessary stations that minimize the uncertainty in the streamflow records for given operating budgets. Kalman-filtering techniques are used to compute uncertainty functions (relating the standard errors of computation or estimation of streamflow records to the frequencies of visits to the stream gages) for all stations in the analysis. A steepest descent optimization program uses these uncertainty functions, information on practical stream-gaging routes, the various costs associated with stream gaging, and the total operating budget to identify the visit frequency for each station that minimizes the overall uncertainty in the streamflow. The standard errors of estimate given in the report are those that would occur if daily discharges were computed through the use of methods described in this study. No attempt has been made to estimate standard errors for discharges that are computed by other means. Such errors could differ from the errors computed in the report. The magnitude and direction of the differences would be a function of methods used to account for shifting controls and for estimating discharges during periods of missing record. The stream-gaging program that results from this analysis will meet the expressed water-data needs in the most cost-effective manner.

This report is organized into five sections; the first being an introduction to the stream-gaging activities in the Hawaii District and to the study itself. The middle three sections each contain discussions of an individual step of the analysis. Because of the sequential nature of the steps and the dependence of subsequent steps on the previous results, conclusions are made at the end of each of the middle three sections. The study, including all conclusions, is summarized in the final section.

History of the Stream-Gaging Program in the Hawaii District

The program of surface-water investigations by the USGS in the Hawaii District has grown rather steadily through the years as Federal and State interests in water resources increased. The Hawaii office of the USGS began collecting surface-water data in what is now the State of Hawaii with the establishment of

12 gaging stations in 1909. These first stations were operated primarily to evaluate the potential of the streams for supplying the irrigational needs of the sugar industry. From this modest beginning, the program rapidly expanded to the point where, in 1914, the USGS operated 87 gaging stations in the State. During the next 25 years, the program operated by the Hawaii District gradually increased to 143 gaging stations. Although a small decrease of the program occurred during the period 1941 to 1950, by 1968 the USGS was operating 240 daily flow surface-water gaging stations within the Hawaii District. This was the highest number of stations ever operated by the Hawaii District. During this period new programs outside of the State were started. Gaging stations on Guam were started in 1952, American Samoa in 1958, and Okinawa in 1963.

Between 1968 and 1983, there was a net reduction of 116 continuous stream gages from the Hawaii District gaging program, although a new program in the Trust Territory of the Pacific Islands was started in 1968. Decisions to drop the gages were based on various economic, technical and political reasons. These reductions leave the Hawaii District program with 124 stations in 1983.

The historical number of continuous stream gages operated within the Hawaii District is given in figure 1.

Current Hawaii District Stream-Gaging Program

The stream-gaging network in the Hawaii District is spread across vast areas in the Pacific Ocean. The locations of these areas and their political entities are shown in plates 1 and 2. Ninety-two gages are located in the State of Hawaii, 2 are located in the Commonwealth of the Marianas Island, 7 are in Guam, 4 are in Palau, 12 are in the Federated States of Micronesia, and 7 are located in American Samoa. Thirty-two gages located in areas other than the State of Hawaii will be grouped as stations in the 'Other Pacific Areas'. There are parts of some islands in which streamflow data sites seem too sparse to provide valid estimates of streamflow characteristics. This paucity was caused by discontinuance of gages in the past for economic, technical and political reasons. The cost of operating the 124 stream gages in fiscal year 1983 is $570,620.

Selected hydrologic data, including drainage area, period of record, and mean annual flow, for the 124 stations are given in table 1. Station identification numbers used throughout this report are abbreviated from the USGS's

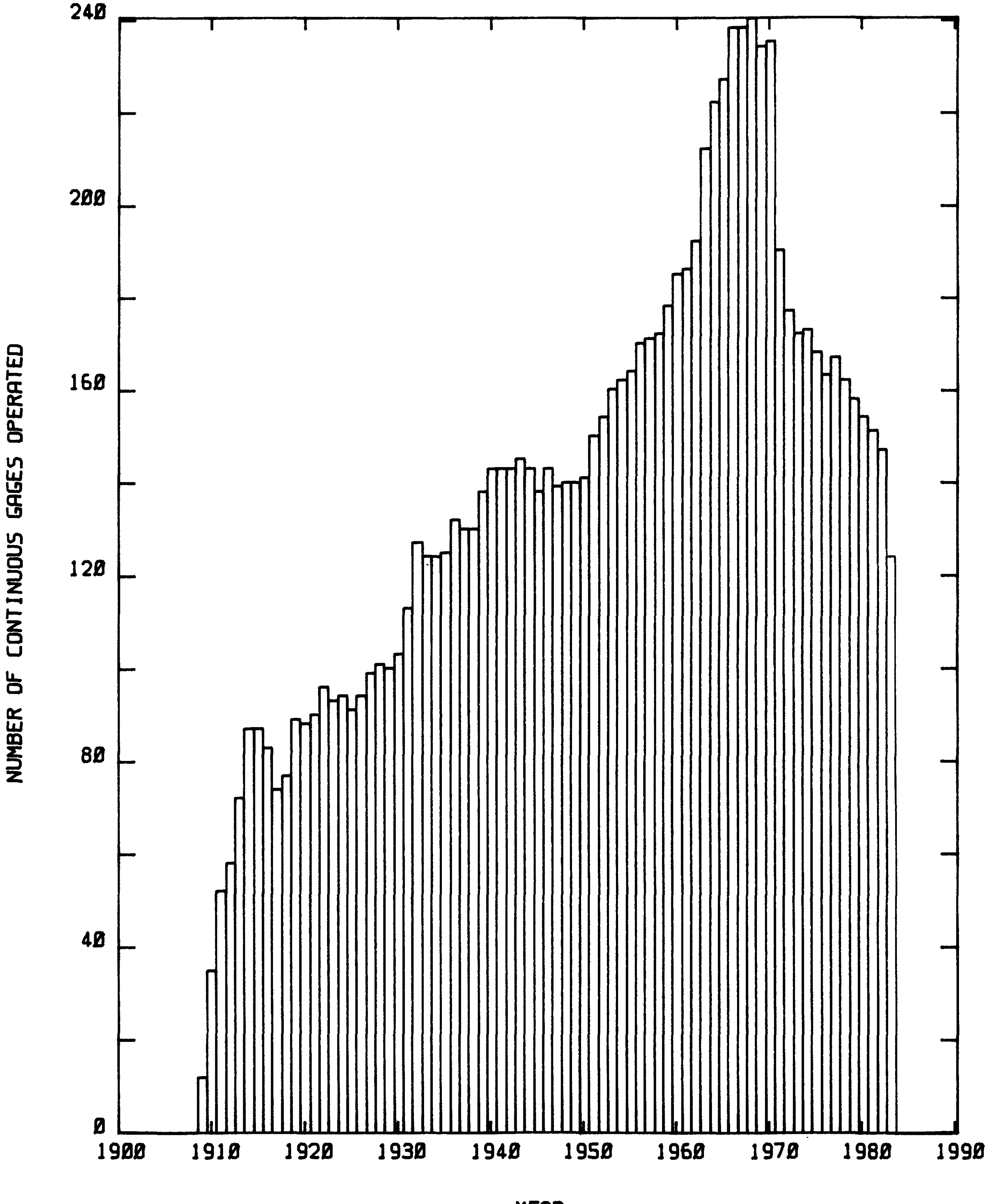

Figure 1. History of continuous stream gaging in the Hawaii District.

Table 1.--Selected hydrologic data for stations in the Hawaii District surface-water program

Station no. 16-	Station name	Abbreviated station name	Drainage area (mi^2)	Period of record	Mean annual flow (ft^3/s)
STATE OF HAWAII					
ISLAND OF KAUAI					
010000	Kawaikoi Stream near Waimea	(Kawaikoi)	3.95	1909-1916, 1919-	34.2
019000	Waialae Stream at altitude 3,282 ft. (1,164 m), near Waimea	(Waialae)	1.79	1920-1932, 1952-	22.0
031000	Waimea River near Waimea	(Waimea)	57.8	1910-1919, 1943-	126
036000	Makaweli River near Waimea	(Makaweli)	26.0	1943-	85.7
049000	Hanapepe River below Manuahi Stream, near Eleele	(Hanapepe)	18.5	1917-1921, 1926-	85.4
060000	South Fork Wailua River near Lihue	(South Wailua)	22.4	1911-	115
061000	North Wailua Ditch near Lihue	(Ditch Lihue)	--	1932-	18.8
061200	North Wailua Ditch below Waikoko Stream, near Lihue	(Ditch Waikoko)	--	1965-	23.5
062000	Stable storm ditch near Lihue	(Stable)	--	1936-	10.7
063000	North Fork Wailua River at altitude 650 ft. (198 m) near Lihue	(North Wailua Lihue)	5.29	1914-	72.9
068000	East Branch of North Fork Wailua River near Lihue	(East Wailua)	6.27	1912-	48.0
069000	Wailua Ditch near Kapaa	(Wailua Ditch)	--	1936-	15.3
071000	North Fork Wailua River near Kapaa	(North Wailua Kapaa)	17.9	1952-	125
071500	Left Branch Opaekaa Stream near Kapaa	(Opaekaa)	.65	1960-	2.58
077000	Makaleha Ditch near Kealia	(Makaleha)	--	1936	6.76
079000	Kapahi Ditch near Kealia	(Kapahi)	--	1909-	6.32
080000	Kapaa Stream at Kapahi Ditch intake, near Kapaa	(Kapaa)	3.86	1936-	20.1
087000	Anahola Ditch wasteway near Kealia	(Anahola wasteway)	--	1936-	4.38
088000	Anahola Ditch above Kaneha reservoir near Kealia	(Anahola Kaneha)	--	1921-	4.17
089000	Anahola Stream near Kealia	(Anahola)	4.27	1910, 1913-	22.5
091000	Lower Anahola Ditch near Kealia	(Lower Anahola)	--	1936-	2.98
097500	Halaulani Stream at altitude 400 ft. (122 m) near Kilauea	(Halaulani)	1.19	1957-	11.3
100000	Hanalei Tunnel outlet near Lihue	(Tunnel outlet)	--	1932-	27.3
103000	Hanalei River near Hanalei	(Hanalei)	19.1	1912-1919, 1962-	214
108000	Wainiha River near Hanalei	(Wainiha)	10.2	1952-	137
ISLAND OF OAHU					
200000	North Fork Kaukonahua Stream above right branch near Wahiawa	(North Kaukonahua)	1.38	1913-1953, 1960-	16.4
208000	South Fork Kaukonahua Stream at east pump reservoir, near Wahiawa	(South Kaukonahua)	4.04	1957-	21.5
211600	Makaha Stream near Makaha	(Makaha)	2.31	1959-	1.88
212800	Kipapa Stream near Wahiawa	(Kipapa)	4.29	1957-	10.7
213000	Waikele Stream at Waipahu	(Waikele)	45.7	1951-	38.0
216000	Waiawa Stream near Pearl City	(Waiawa)	26.4	1957-	33.1
226000	North Halawa Stream near Aiea	(North Halawa)	3.45	1929-1933, 1953-	4.90
229000	Kalihi Stream near Honolulu	(Kalihi Honolulu)	2.61	1913-	6.71
229300	Kalihi Stream at Kalihi	(Kalihi Kalihi)	5.18	1962-	10.9
232000	Nuuanu Stream below reservoir 2 wasteway, near Honolulu	(Nuuanu)	3.35	1913-	7.04
240500	Waiakeakua Stream at Honolulu	(Waiakeakua)	1.06	1913-1921, 1925-	5.06
254000	Makawao Stream near Kailua	(Makawao)	2.04	1912-1916, 1958-	4.96
272200	Kamooalii Stream below Luluku Stream near Kaneohe	(Kamooalii)	3.81	1976-	17.9
283600	South Fork Waihee Stream near Heeia	(South Waihee)	.03	1962-	1.67
283700	North Fork Waihee Stream near Heeia	(North Waihee)	.03	1962-	1.75
284200	Waihee Stream near Kahaluu	(Waihee)	.97	1974-	5.22
294900	Waikane Stream at altitude 75 ft. (23 m), at Waikane	(Waikane)	2.22	1959-	8.30
296500	Kahana Stream at altitude 30 ft. (9.1 m), near Kahana	(Kahana)	3.74	1958-	31.7
302000	Punaluu Ditch near Punaluu	(Punaluu Ditch)	--	1953-	7.76
303000	Punaluu Stream near Punaluu	(Punaluu)	2.78	1953-	17.2
304200	Kaluanui Stream near Punaluu	(Kaluanui)	1.11	1967-	3.90
325000	Kamananui Stream at Pupukea military road, near Maunawai	(Kamananui Pupukea)	3.13	1963-	10.4
330000	Kamananui Stream at Maunawai	(Kamananui Maunawai)	12.4	1958-	16.6
345000	Opaeula Stream near Wahiawa	(Opaeula)	2.98	1959-	13.3

Table 1.--Selected hydrologic data for stations in the Hawaii District surface-water program--Continued

Station no. 16-	Station name	Abbreviated station name	Drainage area (mi^2)	Period of record	Mean annual flow (ft^3/s)
ISLAND OF MOLOKAI					
400000	Halawa Stream near Halawa	(Halawa)	4.62	1917-1932, 1937-	29.1
404200	Pilipililau Stream near Pelekunu	(Pilipililau)	.49	1968-	1.45
405100	Molokai Tunnel at East Portal	(Tunnel east)	--	1966-	3.09
405300	Molokai Tunnel at West Portal	(Tunnel west)	--	1965-	5.44
405500	Waikolu Stream at altitude 900 ft. (274 m), near Kalaupapa	(Waikolu)	1.99	1956-	7.22
408000	Waikolu Stream below pipeline crossing, near Kalaupapa	(Waikolu pipeline)	3.68	1919-1932, 1937-	15.2
414000	Kaunakakai Gulch at Kaunakakai	(Kaunakakai)	6.57	1949-	1.55
419500	Papio Gulch at Halawa	(Papio)	.94	1963-	.76
ISLAND OF MAUI					
501000	Palikea Stream below diversion dam, near Kipahulu	(Palikea)	6.29	1927-1929, 1931-	57.1
508000	Hanawi Stream near Nahiku	(Hanawi)	3.49	1914-1916, 1921-	22.8
512000	Koolau Ditch at Nahiku weir, near Nahiku	(Koolau Nahiku)	--	1919-	33.9
518000	West Wailuaiki Stream near Keanae	(Wailuaiki)	3.66	1914-1917, 1921-	35.1
523000	Koolau Ditch near Keanae	(Koolau Keanae)	--	1910-1912, 1917-	101
531000	Kula Diversion from Haipuaena Stream near Olinda	(Kula)	--	1945-	.72
538000	Spreckels Ditch at Haipuaena weir, near Huelo	(Spreckels)	--	1922-	28.9
541000	Koolau Ditch at Haipuena near Huelo	(Koolau Haipuena)	--	1922-	115
541500	Manuel Luis Ditch at Puohokamoa Gulch, near Huelo	(Manuel)	--	1917-	8.21
587000	Honopou Stream near Huelo	(Honopou)	.64	1910-	4.66
588000	Wailoa Ditch at Honopou, near Huelo	(Wailoa)	--	1922-	170
589000	New Hamakua Ditch at Honopou, near Huelo	(Hamakua Honopou)	--	1918-	36.0
592000	Lowrie Ditch at Honopou Gulch, near Huelo	(Lowrie)	--	1910-1927, 1930-	36.9
594000	Haiku Ditch at Honopou Gulch, near Kailua	(Haiku)	--	1910-1928, 1930-	24.6
599500	Opana Tunnel at Kailiili	(Opana)	--	1965-	2.89
618000	Kahakuloa Stream near Honokohau	(Kahakuloa)	3.47	1939-1943, 1947-1970, 1974-	17.0
620000	Honokohau Stream near Honokohau	(Honokohau)	4.11	1911, 1913-1920,1922-	39.3
638500	Kahoma Stream at Lahaina	(Kahoma)	5.22	1962-	3.47
ISLAND OF HAWAII					
700000	Waiakea Stream near Mountain View	(Waiakea)	17.4	1930-	11.8
700900	Olaa Flume Spring near Kaumana	(Olaa)	--	1974-	9.53
700950	Lyman Springs No. 2 near Piihonua	(Lyman)	--	1981-	1/
704000	Wailuku River at Piihonua	(Wailuku Piihonua)	230	1928-	284
713000	Wailuku River at Hilo	(Wailuku Hilo)	256	1977-	1/
717000	Honolii Stream near Papaikou	(Honolii)	11.6	1911-1913, 1967-	126
720000	Kawainui Stream near Kamuela	(Kawainui)	1.58	1964-	14.4
720300	Kawaiki Stream near Kamuela	(Kawaiki)	.45	1968-	4.21
720500	Upper Hamakua Ditch below Kawaiki Stream, near Kamuela	(Hamakua Kawaiki)	--	1964-	7.69
724800	Upper Hamakua Ditch above Alakahi Stream, near Kamuela	(Hamakua Alakahi)	--	1968-	5.13
725000	Alakahi Stream near Kamuela	(Alakahi)	.87	1964-	6.66
726000	Upper Hamakua Ditch above Waimea reservoir diversion, near Kamuela	(Hamakua Waimea)	--	1974-	9.21
727000	Upper Hamakua Ditch above Puukapu reservoir, near Kamuela	(Hamakua Puukapu)	--	1977-	1.84
756000	Kohakohau Stream near Kamuela	(Kohakohau)	2.51	1956-	8.61
758000	Waikoloa Stream at marine dam, near Kamuela	(Waikoloa)	1.18	1947-	8.82
759000	Hauani Gulch near Kamuela	(Hauani)	.47	1956-	1.55
764000	Hilea Gulch tributary near Honuapo	(Hilea)	9.17	1966-	8.72

See footnote at end of table, p. 8.

Table 1.--Selected hydrologic data for stations in the Hawaii District surface-water program--Continued

Station no. 16-	Station name	Abbreviated station name	Drainage area (mi²)	Period of record	Mean annual flow (ft³/s)
OTHER PACIFIC AREAS					
ISLAND OF SAIPAN					
800000	Denni Spring	(Denni)	--	1952-1954, 1968-	0.64
801000	South Fork Talofofo Stream	(Talofofo)	0.69	1968-	1.46
ISLAND OF GUAM					
809600	La Sa Fua River near Umatac	(La Sa Fua)	1.06	1953-1960, 1976-	4.45
840000	Tinaga River near Inarajan	(Tinaga)	1.89	1952-	5.64
847000	Imong River near Agat	(Imong)	1.95	1960-	10.2
848100	Almagosa River near Agat	(Almagosa)	1.32	1972-	6.40
848500	Maulap River near Agat	(Maulap)	1.15	1972-	5.30
854500	Ugum River above Talofofo falls, near Talofofo	(Ugum)	5.76	1977-	25.4
858000	Ylig River near Yona	(Ylig)	6.48	1952-	28.7
ISLAND OF BABELTHUAP					
890600	Diongradid River, Babelthuap	(Diongradid)	4.45	1969-	33.6
890900	Tabecheding River, Babelthuap	(Tabecheding)	6.07	1970-	49.5
891310	Kmekumel River, Babelthuap	(Kmekumel)	1.44	1978-	1/
891400	South Fork Ngerdorch River, Babelthuap	(Ngerdorch)	2.44	1971-	19.9
ISLAND OF YAP					
892000	Qatliw Stream, Yap	(Qatliw)	.31	1982-	1/
892400	Qaringeel Stream, Yap	(Qaringeel)	.24	1968-	1.10
893100	Burong Stream, Yap	(Burong)	.23	1968-	.94
ISLAND OF GAGIL-TAMIL					
893200	Mukong Stream, Gagil-Tamil	(Mukong)	.50	1974-	1.88
893400	Eyeb Stream, Gagil-Tamil	(Eyeb)	.22	1982-	1/
ISLAND OF MOEN					
893800	Wichen River at altitude 18m, Moen	(Wichen)	.57	1955-1956, 1968-	3.02
ISLAND OF PONAPE					
897600	Nanpil River	(Nanpil)	3.00	1970-	47.5
897900	Lewi River	(Lewi)	.46	1970-	5.44
898600	Luhpwor River	(Luhpwor)	.72	1972-	8.98
ISLAND OF KOSRAE					
899620	Melo River	(Melo)	.68	1974-	6.37
899750	Malem River	(Malem)	.76	1971-	7.17
899800	Tofol River	(Tofol)	.53	1971-	5.93
ISLAND OF TUTUILA					
912000	Pago Stream at Afono	(Pago)	.60	1958-	3.47
920500	Aasu Stream at Aasu	(Aasu)	1.03	1958-	6.12
931000	Atauloma Stream at Afao	(Atauloma)	.24	1958-	1.45
931500	Asili Stream at altitude 330 ft. (101 m) near Asili	(Asili)	.32	1977-	2.76
933500	Leafu Stream at altitude 370 ft. (113 m) near Leone)	(Leafu Leone)	.31	1977-	4.99
948000	Afuelo Stream at Matuu	(Afuelo)	.25	1958-	1.49
963900	Leafu Stream near Auasi	(Leafu Auasi)	.11	1972-	.37

1/ No mean annual flow published, less than 5 years of streamflow record.

eight-digit downstream-order station number; six digit numbers are used by dropping the first two digits (16) of the standard USGS station number for all stations used in this report since they are the same. Table 1 also provides the official name of each stream gage, as well as an abbreviated version of each name. Abbreviated names will be used in the remainder of this report.

USES, FUNDING, AND AVAILABILITY OF CONTINUOUS STREAMFLOW DATA

The relevance of a stream gage is defined by the uses that are made of the data that are produced from the gage. The uses of the data from each gage in the Hawaii District program were identified by a survey of known data users and past inquiries. Each data use thus identified was categorized into one of nine known classes of data uses defined below.

Data-Use Classes

The following definitions were used to categorize each known use of streamflow data for each continuous stream gage.

Regional Hydrology

For data to be useful in defining regional hydrology, a stream gage must be largely unaffected by manmade storage or diversion. In this class of uses, the effects of man on streamflow are not necessarily small, but the effects are limited to those caused primarily by land-use and climate changes. Large amounts of manmade storage may exist in the basin providing the outflow is uncontrolled. These stations are useful in developing regionally transferable information about the relationship between basin characteristics and streamflow.

Fifty-six stations in the Hawaii District network are classified in the regional hydrology data-use category. Five of the stations are special cases in that they are designated bench-mark or index stations. There is one hydrologic bench-mark station in Hawaii which serves as an indicator of hydrologic conditions in watersheds relatively free of manmade alteration. Four index stations located in different regions of the State are used to indicate current hydrologic conditions. The locations of stream gages that provide information about regional hydrology are given in plates 1 and 2.

Hydrologic Systems

Stations that can be used for accounting, that is, to define current hydrologic conditions and the sources, sinks, and fluxes of water through hydrologic systems including regulated systems, are designated as hydrologic systems stations. They include diversions and return flows and stations that are useful for defining the interaction of water systems.

The bench-mark and index stations are also included in the hydrologic systems category because they are accounting for current and long-term conditions of the hydrologic systems that they gage.

There are sixty-five stations in the Hawaii District program that are being operated to evaluate hydrologic systems.

Legal Obligations

Some stations provide records of flows for the verification or enforcement of existing treaties, compacts, and decrees. The legal obligation category contains only those stations that the USGS is required to operate to satisfy a legal responsibility.

There are no stations in the Hawaii District program that exist to fulfill a legal responsibility of the USGS.

Planning and Design

Gaging stations in this category of data use are used for the planning and design of a specific project (for example, a dam, levee, floodwall, navigation system, water-supply diversion, hydropower plant, or waste-treatment facility) or group of structures. The planning and design category is limited to those stations that were instituted for such purposes and where this purpose is still valid.

Currently, one station in the Hawaii District program is being operated for planning and design purposes.

Project Operation

Gaging stations in this category are used, on an ongoing basis, to assist water managers in making operational decisions such as reservoir releases, hydropower operations, or diversions. The project operation use generally implies that the data are routinely available to the operators on a rapid-reporting basis. For projects on large streams, data may only be needed every few days.

There are no stations in the Hawaii District program that are used in this manner.

Hydrologic Forecasts

Gaging stations in this category are regularly used to provide information for hydrologic forecasting. These might be flood forecasts for a specific river reach, or periodic (daily, weekly, monthly, or seasonal) flow-volume forecasts for a specific site or region. The hydrologic forecast use generally implies that the data are routinely available to the forecasters on a rapid-reporting basis. On large streams, data may only be needed every few days.

There are no stations in the Hawaii District program that are in the hydrologic forecast category.

Water-Quality Monitoring

Gaging stations where regular water-quality or sediment-transport monitoring is being conducted and where the availability of streamflow data contributes to the utility or is essential to the interpretation of the water-quality or sediment data are designated as water-quality-monitoring sites.

One such station in the program is a designated bench-mark station and six are National Stream Quality Accounting Network (NASQAN) stations. Water-quality samples from bench-mark stations are used to indicate water-quality characteristics of streams that have been and probably will continue to be relatively free of manmade influence. NASQAN stations are part of a country-wide network designed to assess water-quality trends of significant streams.

Research

Gaging stations in this category are operated for a particular research or water-investigations study. Typically, these are only operated for a few years.

There are no stations in the Hawaii District program used in the support of research activities.

Other

In addition to the eight data-use classes described above, data in this category are used to provide information on floods by furnishing flood hydrographs peak stages and discharges to the cooperator. There are five such stations in the Hawaii District program.

Funding

The three sources of funding for the streamflow-data program are:

1. Federal program.--Funds that have been directly allocated to the USGS.

2. Other Federal Agency (OFA) program.--Funds that have been transferred to the USGS by OFA's.

3. Co-op program.--Funds that come jointly from USGS cooperative-designated funding and from any non-Federal cooperating agency. Cooperating agency funds may be in the form of direct services or cash.

In all three categories, the identified sources of funding pertain only to the collection of streamflow data; sources of funding for other activities, particularly collection of water-quality samples, that might be carried out at the site may not necessarily be the same as those identified herein.

Currently, 13 entities are contributing funds to the Hawaii District stream-gaging program.

Frequency of Data Availability

Frequency of data availability refers to the times at which the streamflow data may be furnished to the users. In this category, three distinct possibilities exist. Data can be furnished by direct-access telemetry equipment for immediate use, by periodic release of provisional data, or in publication format through the annual data report published by the USGS for Hawaii and Other Pacific Areas (U.S. Geological Survey, 1981). In the current Hawaii District program, data for all 124 stations are made available through the annual report and is designated A in table 2.

Data-Use Presentation

Data-use and ancillary information are presented for each continuous gaging station in table 2, which is replete with footnotes to expand the information conveyed. The entry of an asterisk in the table indicates that no footnote is required.

Conclusions Pertaining to Data Uses

A review of the data-use and funding information presented in table 2 supports the continuation of all the existing stations. Therefore, all the 124 gaging stations will be considered in the next step of this analysis.

Table 2.--Data-use table

Station no.	DATA USE									FUNDING			Frequency of Data Availability
	Regional Hydrology	Hydrologic Systems	Legal Obligations	Planning and Design	Project Operation	Hydrologic Forecasts	Water-Quality Monitoring	Research	Other	Federal Program	OFA Program	Co-Op Program	
STATE OF HAWAII													
010000	*	4										2	A
019000	*	*								*			A
031000							6			*			A
036000		*										2	A
049000		*										2	A
060000		*										2	A
061000		3										2	A
061200		3										2	A
062000		4										2	A
063000		*										2	A
068000	1	1, 4										2	A
069000		4										2	A
071000									5		7		A
071500	*											2	A
077000		4										2	A
079000		4										2	A
080000		*										2	A
087000		*										2	A
088000		4										2	A
089000		*										2	A
091000		4										2	A
097500	*											2	A
100000		4										2	A
103000									5		7		A
108000	*											2	A

1 Long-term index gaging station.
2 State of Hawaii.
3 Power and irrigation use.
4 Irrigation use.
5 Monitoring of flood data.
6 NASQAN station.
7 U.S. Corps of Engineers.

Table 2.--Data-use table--Continued

Station no.	DATA USE: Regional Hydrology	Hydrologic Systems	Legal Obligations	Planning and Design	Project Operation	Hydrologic Forecasts	Water-Quality Monitoring	Research	Other	FUNDING: Federal Program	OFA Program	Co-Op Program	Frequency of Data Availability
200000	*											2	A
208000	*											2	A
211600	*											2	A
212800	*											2	A
213000							6			*			A
216000	*											2	A
226000	*											2	A
229000	1	1										2	A
229300							6		5	*	7		A
232000		*										9	A
240500		*										9	A
254000		*										2	A
272200							8				7		A
283600		*										9	A
283700		*										9	A
284200		*										9	A
294900	*											2	A
296500	*											2	A
302000		4										9	A
303000		*										9	A
304200	*											9	A
325000	*											9	A
330000	*											2	A
345000	*											2	A

1 Long-term index station.
2 State of Hawaii.
4 Irrigation use.
5 Monitoring of flood data.
6 NASQAN station.
7 U.S. Corps of Engineers.
8 Sediment transport.
9 City and County of Honolulu - Board of Water Supply.

Table 2.--Data-use table--Continued

Station no.	DATA USE									FUNDING			
	Regional Hydrology	Hydrologic Systems	Legal Obligations	Planning and Design	Project Operation	Hydrologic Forecasts	Water-Quality Monitoring	Research	Other	Federal Program	OFA Program	Co-Op Program	Frequency of Data Availability
400000	*						6					2	A
404200	*											2	A
405100		4										2	A
405300		4										2	A
405500		*										2	A
408000		*										2	A
414000									5		7		A
419500	*											2	A
501000	*											2	A
508000	*											2	A
512000		10										2	A
518000	*											2	A
523000		10										2	A
531000		11										2	A
538000		11										2	A
541000		10										2	A
541500		4										2	A
587000	1	1										2	A
588000		10										2	A
589000		4										2	A
592000		4										2	A
594000		4										2	A
599500		*										2	A
618000							6			*			A
620000	*											2	A
638500									5		7		A

1 Long-term index station.
2 State of Hawaii.
4 Irrigation use.
5 Monitoring of flood data.
6 NASQAN station.
7 U.S. Corps of Engineers.
10 Power, irrigation, and domestic use.
11 Irrigation and domestic use.

Table 2.--Data-use table--Continued

Station no.	DATA USE									FUNDING			Frequency of Data Availability
	Regional Hydrology	Hydrologic Systems	Legal Obligations	Planning and Design	Project Operation	Hydrologic Forecasts	Water-Quality Monitoring	Research	Other	Federal Program	OFA Program	Co-Op Program	
700000	1	1										2	A
700900		12										2	A
700950		*										2	A
704000		*										2	A
713000							6			*			A
717000	13	13					13			*			A
720000		*										2	A
720300		*										2	A
720500		4										2	A
724800		4										2	A
725000		*										2	A
726000		4										2	A
727000		4										2	A
756000		*										2	A
758000		*										2	A
759000		*										2	A
764000	*											2	A

1 Long-term index station.
2 State of Hawaii.
4 Irrigation use.
6 NASQAN station.
12 Domestic use.
13 Hydrologic benchmark station.

Table 2.--Data-use table--Continued

Station no.	DATA USE									FUNDING			
	Regional Hydrology	Hydrologic Systems	Legal Obligations	Planning and Design	Project Operation	Hydrologic Forecasts	Water-Quality Monitoring	Research	Other	Federal Program	OFA Program	Co-Op Program	Frequency of Data Availability
OTHER PACIFIC AREAS													
800000		*										14	A
801000	*											14	A
809600	*											15	A
840000	*											15	A
847000		*									16		A
848100		*									16		A
848500		*									16		A
854500				17							7		A
858000	*											15	A
890600	*											18	A
890900	*											18	A
891310	*											18	A
891400	*											18	A
892000	*											19	A
892400	*											19	A
893100	*											19	A
893200	*											19	A
893400	*											19	A
893800	*											20	A
897600	*											21	A

7 U.S. Corps of Engineers.
14 Commonwealth of the Northern Mariana Islands.
15 Territory of Guam.
16 U.S. Navy.
17 Possible plans for dam.
18 Republic of Palau.
19 Government of Yap.
20 Government of Truk.
21 Government of Ponape.

Table 2.--Data-use table--Continued

Station no.	DATA USE									FUNDING			Frequency of Data Availability
	Regional Hydrology	Hydrologic Systems	Legal Obligations	Planning and Design	Project Operation	Hydrologic Forecasts	Water-Quality Monitoring	Research	Other	Federal Program	OFA Program	Co-Op Program	
897900	*											21	A
898600	*											21	A
899620	*											22	A
899750	*											22	A
899800	*											22	A
912000	*											23	A
920500	*											23	A
931000	*											23	A
931500		*										23	A
933500		*										23	A
948000	*											23	A
963900	*											23	A

21 Government of Ponape.
22 Government of Kosrae.
23 Government of American Samoa.

ALTERNATIVE METHODS OF DEVELOPING STREAMFLOW INFORMATION

The second step of the analysis of the stream-gaging program is to investigate alternative methods of providing daily streamflow information in lieu of operating continuous-flow gaging stations. The objective of the analysis is to identify gaging stations where alternative technology, such as flow-routing or statistical methods, will provide information about daily mean streamflow in a more cost-effective manner than operating a continuous stream gage. No guidelines concerning suitable accuracies exist for particular uses of the data; therefore, judgment is required in deciding whether the accuracy of the estimated daily flows is suitable for the intended purpose. The data uses at a station will influence whether a site has potential for alternative methods. For example, those stations for which flood hydrographs are required in a real-time sense, such as hydrologic forecasts and project operation, are not candidates for the alternative methods. Likewise, there might be a legal obligation to operate an actual gaging station that would preclude utilizing alternative methods. The primary candidates for alternative methods are stations that are operated upstream or downstream of other stations on the same stream. The accuracy of the estimated streamflow at these sites may be suitable because of the high redundancy of flow information between sites. Similar watersheds, located in the same physiographic and climatic area, also may have potential for alternative methods.

All stations in the Hawaii District stream-gaging program were categorized as to their potential utilization of alternative methods and one selected method was applied at seven stations. The selection of gaging stations and the application of the specific method are described in subsequent sections of this report. This section briefly describes the alternative method used in the Hawaii District analysis and documents why this specific method was chosen.

Because of the short timeframe of this analysis, only two methods were considered: multiple-regression analysis and flow-routing model. Desirable attributes of a proposed alternative method are (1) the proposed method should be computer oriented and easy to apply, (2) the proposed method should have an available interface with the USGS WATSTORE Daily Values File (Hutchinson, 1975), (3) the proposed method should be technically sound and generally acceptable to the hydrologic community, and (4) the proposed method should permit easy evaluation of the accuracy of the simulated streamflow records. The desirability of the first attribute above is rather obvious. Second, the interface with the WATSTORE Daily Values File is needed to easily calibrate the proposed alternative method. Third, the alternative method selected for analysis must be technically sound or it will not be able to provide data of suitable accuracy. Fourth, the alternative method should provide an estimate of the accuracy of the streamflow to judge the adequacy of the simulated data.

The time of travel of flow between upstream and downstream gaging stations in the Hawaii District is measured in hours, often in minutes, rather than days. This together with the fact that there are few streams with upstream and downstream gages made the flow-routing model impractical. Therefore, of the two methods that were considered only the multiple regression analysis was used.

Description of Regression Analysis

Simple- and multiple-regression techniques can be used to estimate daily flow records. Regression equations can be computed that relate daily flows (or their logarithms) at a single station to daily flows at a combination of upstream, downstream, and (or) tributary stations. This statistical method is not limited, like the flow-routing method, to stations where an upstream station exists on the same stream. The explanatory variables in the regression analysis can be stations from different watersheds, or downstream and tributary watersheds. The regression method has many favorable attributes in that it is easy to apply, provides indices of accuracy, and is generally accepted as a good tool for estimation. The theory and assumptions of regression analysis are described in several textbooks such as those by Draper and Smith (1966) and Kleinbaum and Kupper (1978). The application of regression analysis to hydrologic problems is described and illustrated by Riggs (1973) and Thomas and Benson (1970). Only a brief description of regression analysis is provided in this report.

A linear regression model of the following form was developed for estimating daily mean discharge in the Hawaii District:

$$Y_i = B_o + \sum_{j=1}^{p} B_j x_j + e_i$$

where

y_i = daily mean discharge at station i (dependent variable),

x_j = daily mean discharges at nearby stations (explanatory variables),

B_o and B_j = regression constant and coefficients,

e_i = the random error term, and

p = number of nearby stations (explanatory variables) used in the model.

The above equation is calibrated (B_o and B_j are estimated) using observed values of y_i and x_j. These observed daily mean discharges can be retrieved from the WATSTORE Daily Values File. The values of x_j may be discharges observed on the same day as discharges at station i or may be for previous or future days, depending on whether station j is upstream or downstream of station i. Once the equation is calibrated and verified, future values of y_i are estimated using observed values of x_j. The regression constant and coefficients (B_o and B_j) are tested to determine if they are significantly different from zero. A given station j should only be retained in the regression equation if its regression coefficient (B_j) is significantly different from zero. The regression equation should be calibrated using one period of time and then verified or tested on a different period of time to obtain a measure of the true predictive accuracy. Both the calibration and verification period should be representative of the range of flows that could occur at station i.

The equation should be verified by (1) plotting the residuals e_i (difference between simulated and observed discharges) against the dependent and all explanatory variables in the equation, and (2) plotting the simulated and observed discharges versus time. These tests are intended to identify if (1) the linear model is appropriate or whether some transformation of the variables is needed, and (2) there is any bias in the equation such as overestimating low flows. These tests might indicate, for example, that a logarithmic transformation is desirable, that a nonlinear regression equation is appropriate, or that the regression equation is biased in some way. In this report these tests indicated that a linear model with y_i and x_j, in cubic feet per second, was appropriate. The application of linear-regression techniques to seven watersheds in the Hawaii District is described in a subsequent section of this report.

It should be noted that the use of a regression relation to synthesize data at discontinued gaging station entails a reduction in the variance of the streamflow record relative to that which would be computed from an actual record of streamflow at the site. The reduction in variance expressed as a fraction is approximately equal to one minus the square of the correlation coefficient that results from the regression analysis.

Categorization of Stream Gages by Their Potential for Alternative Methods

Seven stations were selected for analysis because daily discharges at these stations were highly correlated with those for some other stations. These seven stations are Makaweli (036000), North Wailua Kapaa (071000), Hanawi (508000), Koolau Keanae (523000), Wailuku Piihonua (704000), Kawainui (720000), and Kawaiki (720300). It should be noted that a high degree of correlation between stations does not necessarily mean that a high percentage of simulated daily flows will be within a small percentage, such as 10 percent, of the observed flows. Regression methods were applied to all seven sites.

Regression Analysis Results

Linear regression techniques were applied to the seven selected sites. The streamflow record for each station considered for simulation (the dependent variable) was regressed against streamflow records at other stations (explanatory variables) during a given period of record (the calibration period). "Best fit" linear regression models were developed and used to provide a daily streamflow record that was compared to the observed streamflow record. The average percent difference between the simulated and actual record for the indicated period was calculated. The results of the regression analysis for each site are summarized in table 3.

The streamflow record at Makaweli (036000) was not reproduced with an acceptable degree of accuracy using regression techniques. The Makaweli (036000) simulated data were within 10 percent of the actual record only 22 percent of the time during the calibration period. These results occurred when

Table 3.-- Summary of calibration for regression modeling of mean daily streamflow at selected gage sites in the Hawaii District

Station no. and name	Model	Percentage of simulated flow within 5% of actual	Percentage of simulated flow within 10% of actual	Calibration period (water years)
036000 Makaweli	$Q_{036000} = -0.234 + 0.128\ (Q_{031000}) + 0.653\ (Q_{049000}) + 1.77\ (Q_{019000}) - 0.121\ (Q_{108000})$	12	22	1979-82
071000 North Wailua Kapaa	$Q_{071000} = -7.84 + 0.181\ (Q_{060000}) + 0.555\ (Q_{063000}) + 0.872\ (Q_{068000}) + 8.96\ (Q_{071500})$	17	31	Do.
508000 Hanawi	$Q_{508000} = -0.656 + 0.090\ (Q_{501000}) + 0.570\ (Q_{518000}) - 0.128\ (Q_{541500})$	7.8	16	1976-79
523000 Koolau Keanae	$Q_{523000} = 7.35 + 0.872\ (Q_{541000})$	59	88	Do.
704000 Wailuku Piihonua	$Q_{704000} = -21.4 + 0.579\ (Q_{713000}) + 0.392\ (Q_{717000})$	11	22	Do.
720000 Kawainui	$Q_{720000} = -1.17 + 3.04\ (Q_{720300}) - 0.124\ (Q_{725000}) - 0.444\ (Q_{756000})$	9	19	Do.
720300 Kawaiki	$Q_{720300} = 0.792 + 0.188\ (Q_{720000}) + 0.100\ (Q_{725000}) + 0.019\ (Q_{756000})$	13	25	Do.

daily mean discharges at Waialae (019000), Waimea (031000), Hanapepe (049000), and Wainiha (108000) were used as the explanatory variables.

The North Wailua Kapaa (071000) simulated data were within 10 percent of the actual record only 31 percent of the time during the calibration period. These results occurred when daily mean discharges at South Wailua (060000), North Wailua Lihue (063000), East Wailua (068000) and Opaekaa (071500) were used as the explanatory variables. The greatest hindrance to obtaining a satisfactory simulation in this case was that the station was regressed against stations having different flow characteristics at low flows. There is apparent seepage loss between upstream stations and 071000.

The Hanawi (508000) simulated data were within 10 percent of the actual record only 16 percent of the time during the calibration period. These results occurred when daily mean discharges at Palikea (501000), Wailuaiki (518000) and Manuel (541500) were used as the explanatory variables.

The most successful simulation of flow records was at Koolau Keanae (523000) which was produced from regression with another station on the same ditch. The dependent flow records were regressed against downstream ditch records for Koolau Haipuaena (541000). The simulated data were within 10 percent for 88 percent of the calibration period and within 5 percent for 59 percent of the same period. However, verification of the model using different period of data showed that estimated data are considerably less accurate than that of the calibration period. The estimated data were within 10 percent for 66 percent of the verification period and within 5 percent for 34 percent of the same period.

Further improvement in the simulation was attempted by using two separate models, one for high flows ($Q \geq 30$ ft^3/s at Koolau Haipuaena) and one for low flows ($Q < 30$ ft^3/s at Koolau Haipuaena). Using the high- and low-flow models did not improve the simulation. The overall simulation for Koolau Keanae (523000), using the two models, reproduced the actual Koolau Keanae record within 10 percent for 84 percent of the calibration period and within 5 percent for 51 percent of the period.

The Wailuku Piihonua (704000) simulated data were within 10 percent of the actual record only 22 percent of the time during the calibration period. These results occurred when daily mean discharges at Wailuku Hilo (713000) and Honolii (717000) were used as the explanatory variables.

The Kawainui (720000) simulated data were within 10 percent of the actual record only 19 percent of the time during the calibration period. These results occurred when daily mean discharges at Kawaiki (720300), Alakahi (725000) and Kohakohau (756000) were used as the explanatory variables.

The streamflow record for Kawaiki (720300) was simulated with a regression model that includes as explanatory variables, the streamflow at Kawainui (720000), streamflow at Alakahi (725000), and streamflow at Kohakohau (756000). Drainage basins for stations 720000, 720300 and 756000 are located adjacent to each other.

The simulated data for Kawaiki (720300) were within 10 percent of the actual flows for 25 percent of the calibration period and within 5 percent for 13 percent of the period.

Some of the causes for low transferability of flow data among stream gages in the Hawaii District can be attributable to the small drainage areas causing high-flow variability, variability of rainfall distribution among nearby basins, and local differences in basin cover and subsurface materials.

Conclusions Pertaining to Alternative Methods of Data Generation

The simulated data from the regression method for the seven stream gages were not sufficiently accurate to apply this method in lieu of operating a continuous-flow stream gage. It is suggested that all seven stations remain in operation as part of the Hawaii District stream-gaging program; therefore, they will be included in the next step of this analysis.

COST-EFFECTIVE RESOURCE ALLOCATION

Introduction to Kalman-Filtering for Cost-Effective Resource Allocation (K-CERA)

In a study of the cost-effectiveness of a network of stream gages operated to determine water consumption in the Lower Colorado River Basin, a set of techniques called K-CERA were developed (Moss and Gilroy, 1980). Because of the water-balance nature of that study, the measure of effectiveness of the network was chosen to be the minimization of the sum of variances of errors of estimation of annual mean discharges at each site in the network. This measure of effectiveness tends to concentrate stream-gaging resources on the larger, less stable streams where potential errors are greatest. While such a tendency is appropriate for a water-balance network, in the broader context of the multitude of uses of the streamflow data collected in the USGS's Streamflow Information Program, this tendency causes undue concentration on larger streams. Therefore, the original version of K-CERA was extended to include as optional measures of effectiveness the sums of the variances of errors of estimation of the following streamflow variables: annual mean discharge in cubic feet per second, annual mean discharge in percentage, average instantaneous discharge in cubic feet per second, or average instantaneous discharge in percentage. The use of percentage errors does not unduly weight activities at large streams to the detriment of records on small streams. In addition, the instantaneous discharge is the basic variable from which all other streamflow data are derived. For these reasons, this study used the K-CERA techniques with the sums of the variances of the percentage errors of the instantaneous discharges at all continuously gaged sites as the measure of the effectiveness of the data-collection activity.

The original version of K-CERA also did not account for error contributed by missing stage or other correlative data that are used to compute streamflow data. The probabilities of missing correlative data increase as the period between service visits to a stream gage increases. A procedure for dealing with the missing record has been developed and was incorporated into this study.

Brief descriptions of the mathematical program used to optimize cost-effectiveness of the data-collection activity and of the application of Kalman filtering (Gelb, 1974) to the determination of the accuracy of a stream-gaging record are presented below. For more detail on either the theory or the applications of K-CERA, see Moss and Gilroy (1980), Gilroy and Moss (1981), and Fontaine and others (1984).

Description of Mathematical Program

The program, called "The Traveling Hydrographer," attempts to allocate among stream gages a predefined budget for the collection of streamflow data in such a manner that the field operation is the most cost-effective possible. The measure of effectiveness is discussed above. The set of decisions available to the manager is the frequency of use (number of times per year) of each of a number of routes that may be used to service the stream gages and to make discharge measurements. The range of options within the program is from zero usage to daily usage for each route. A route is defined as a set of one or more stream gages and the least cost travel that takes the hydrographer from his base of operations to each of the gages and back to base. A route will have associated with it an average cost of travel and average cost of servicing each stream gage visited along the way. The first step in this part of the analysis is to define the set of practical routes. This set of routes frequently will contain the path to an individual stream gage with that gage as the lone stop and return to the home base so that the individual needs of a stream gage can be considered in isolation from the other gages.

Another step in this part of the analysis is the determination of any special requirements for visits to each of the gages for such things as necessary periodic maintenance, rejuvenation of recording equipment, or required periodic sampling of water-quality data. Such special requirements are considered to be inviolable constraints in terms of the minimum number of visits to each gage.

The final step is to use all of the above to determine the number of times, N_i, that the i^{th} route for i = 1,2, ..., NR, where NR is the number of practical routes, is used during a year such that (1) the budget for the network is not exceeded, (2) the minimum number of visits to each station is made, and (3) the total uncertainty in the network is minimized. Figure 2 represents this step in the form of a mathematical program. Figure 3 presents a tabular layout of the

$$\underset{\underline{N}}{\text{Minimize}}\ V = \sum_{j=1}^{MG} \phi_j\ (M_j)$$

$V \equiv$ total uncertainty in the network

$\underline{N} \equiv$ vector of annual number times each route was used

$MG \equiv$ number of gages in the network

$M_j \equiv$ annual number of visits to station j

$\phi_j \equiv$ function relating number of visits to uncertainty at station j

Such that

Budget $\geq T_c \equiv$ total cost of operating the network

$$T_c = F_c + \sum_{j=1}^{MG} \alpha_j M_j + \sum_{i=1}^{NR} \beta_i N_i$$

$F_c \equiv$ fixed cost

$\alpha_j \equiv$ unit cost of visit to station j

$NR \equiv$ number of practical routes chosen

$\beta_i \equiv$ travel cost for route i

$N_i \equiv$ annual number times route i is used (an element of $\underline{N}$)

and such that

$$M_j \geq \lambda_j$$

$\lambda_j \equiv$ minimum number of annual visits to station j

Figure 2. Mathematical-programing form of the optimization of the routing of hydrographers.

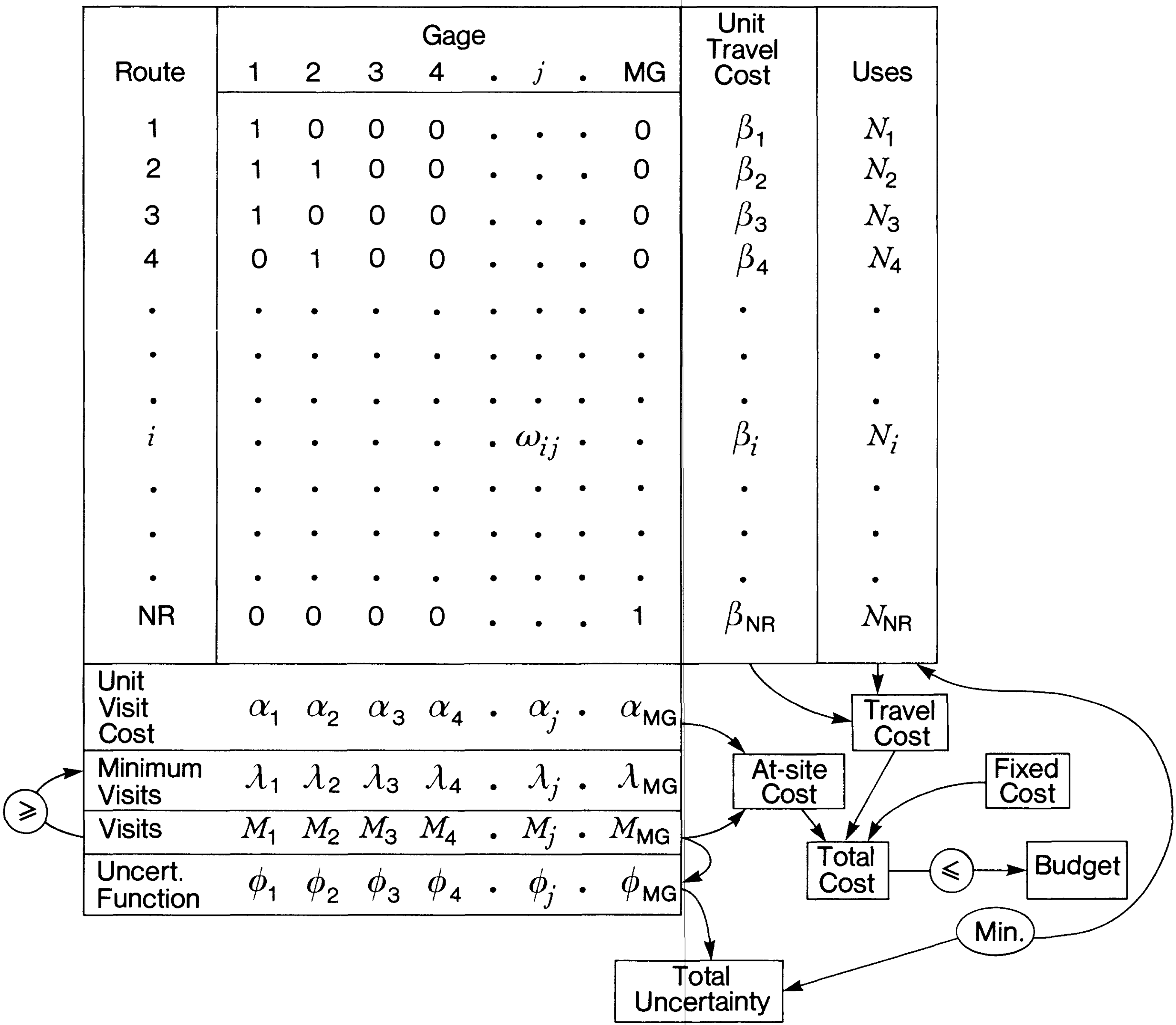

Figure 3. Tabular form of the optimization of the routing of hydrographers.

problem. Each of the NR routes is represented by a row of the table and each of the stations is represented by a column. The zero-one matrix, (ω_{ij}), defines the routes in terms of the stations that comprise it. A value of one in row i and column j indicates that gaging station j will be visited on route i; a value of zero indicates that it will not. The unit travel costs, β_i, are the per-trip costs of the hydrographer's travel time and any related per diem and operation, maintenance, and rental costs of vehicles. The sum of the products of β_i and N_i for i = 1,2, ..., NR is the total travel cost associated with the set of decisions $\underline{N} = (N_1, N_2, \ldots, N_{NR})$.

The unit-visit cost, α_j, is comprised of the average service and maintenance costs incurred on a visit to the station plus the average cost of making a discharge measurement. The set of minimum visit constraints is denoted by the row λ_j, j = 1,2, ..., MG, where MG is the number of stream gages. The row of integers M_j, j = 1,2, ..., MG specifies the number of visits to each station. M_j is the sum of the products of ω_{ij} and N_i for all i and must equal or exceed λ_j for all α_j if $\underline{N}$ is to be a feasible solution to the decision problem.

The total cost expended at the stations is equal to the sum of the products of α_j and M_j for all j. The cost of record computation, documentation, and publication is assumed to be influenced negligibly by the number of visits to the station and is included along with overhead in the fixed cost of operating the network. The total cost of operating the network equals the sum of the travel costs, the at-site costs, and the fixed cost, and must be less than or equal to the available budget.

The total uncertainty in the estimates of discharges at the MG stations is determined by summing the uncertainty functions, ϕ_j, evaluated at the value of M_j from the row above it, for j = 1,2, ..., MG.

As pointed out in Moss and Gilroy (1980), the steepest descent search used to solve this mathematical program does not guarantee a true optimum solution. However, the locally optimum set of values for $\underline{N}$ obtained with this technique specify an efficient strategy for operating the network, which may be the true optimum strategy. The true optimum cannot be guaranteed without testing all undominated, feasible strategies.

Description of Uncertainty Functions

As noted earlier, uncertainty in streamflow records is measured in this study as the average relative variance of estimation of instantaneous discharges. The accuracy of a streamflow estimate depends on how that estimate was obtained. Three situations are considered in this study: (1) streamflow is estimated from measured discharge and correlative data using a stage-discharge relation (rating curve), (2) the streamflow record is reconstructed using secondary data at nearby stations because primary correlative data are missing, and (3) primary and secondary data are unavailable for estimating streamflow. The variances of the errors of the estimates of flow that would be employed in each situation were weighted by the fraction of time each situation is expected to occur. Thus, the average relative variance would be

$$\bar{V} = \varepsilon_f V_f + \varepsilon_r V_r + \varepsilon_e V_e$$

with (3)

$$1 = \varepsilon_f + \varepsilon_r + \varepsilon_e$$

where

$\bar{V}$ is the average relative variance of the errors of streamflow estimates,

ε_f is the fraction of time that the primary recorders are functioning,

V_f is the relative variance of the errors of flow estimates from primary recorders,

ε_r is the fraction of time that secondary data are available to reconstruct streamflow records given that the primary data are missing,

V_r is the relative variance of the errors of estimation of flows reconstructed from secondary data,

ε_e is the fraction of time that primary and secondary data are not available to compute streamflow records, and

V_e is the relative error variance of the third situation.

The fractions of time that each source of error is relevant are functions of the frequencies at which the recording equipment is serviced.

The time, τ, since the last service visit until failure of the recorder or recorders at the primary site is assumed to have a negative-exponential probability distribution truncated at the next service time; the distribution's probability density function is

$$f(\tau) = ke^{-k\tau}/(1-e^{-ks}) \qquad (4)$$

where

- k is the failure rate in units of $(\text{day})^{-1}$,
- e is the base of natural logarithms, and
- s is the interval between visits to the site in days.

It is assumed that if a recorder fails it continues to malfunction until the next service visit. As a result,

$$\varepsilon_f = (1-e^{-ks})/(ks) \qquad (5)$$

(Fontaine and others, 1984, eq. 21).

The fraction of time ε_e that no records exist at either the primary or secondary site can also be derived assuming that the time between failures at both sites are independent and have negative exponential distributions with the same rate constant. It then follows that,

$$\varepsilon_e = 1 - [2(1-e^{-ks}) + 0.5(1-e^{-2ks})]/(ks)$$

(Fontaine and others, 1984, eqs. 23 and 25).

Finally, the fraction of time ε_r that records are reconstructed based on data from a secondary site is determined by the equation,

$$\varepsilon_r = 1 - \varepsilon_f - \varepsilon_e.$$

$$= [(1-e^{-ks}) + 0.5(1-e^{-2ks})]/(ks) \qquad (6)$$

The relative variance, V_f, of the error derived from primary record computation is determined by analyzing a time series of residuals that are the differences between the logarithms of measured discharge and the rating curve discharge. The rating curve discharge is determined from a relationship between discharge and some correlative data such as water-surface elevation at the gaging station. The measured discharge is the discharge determined by field observations of depths, widths, and velocities. Let $q_T(t)$ be the true instantaneous discharge at time t and let $q_R(t)$ be the value that would be estimated using the rating curve. Then,

$$x(t) = \ln q_T(t) - \ln q_R(t) = \ln [q_T(t)/q_R(t)] \qquad (7)$$

is the instantaneous difference between the logarithms of the true discharge and the rating curve discharge.

In computing estimates of streamflow, the rating curve may be continually adjusted on the basis of periodic measurements of discharge. This adjustment process results in an estimate, $q_c(t)$, that is a better estimate of the stream's discharge at time t. The difference between the variable $\hat{x}(t)$, which is defined

$$\hat{x}(t) = \ln q_c(t) - \ln q_R(t) \qquad (8)$$

and $x(t)$ is the error in the streamflow record at time t. The variance of this difference over time is the desired estimate of V_f.

Unfortunately, the true instantaneous discharge, $q_T(t)$, cannot be determined and thus $x(t)$ and the difference, $x(t) - \hat{x}(t)$, cannot be determined as well. However, the statistical properties of $x(t) - \hat{x}(t)$, particularly, its variance, can be inferred from the available discharge measurements. Let the observed residuals of measured discharge from the rating curve be $z(t)$ so that

$$z(t) = x(t) + v(t) = \ln q_m(t) - \ln q_R(t) \qquad (9)$$

where

$v(t)$ is the measurement error, and

$\ln q_m(t)$ is the logarithm of the measured discharge equal to $\ln q_T(t)$ plus $v(t)$.

In the Kalman-filter analysis, the z(t) time series was analyzed to determine three site-specific parameters. The Kalman filter used in this study assumes that the time residuals x(t) arise from a continuous first-order Markovian process that has a Gaussian (normal) probability distribution with zero mean and variance (subsequently referred to as process variance) equal to p. A second important parameter is β, the reciprocal of the correlation time of the Markovian process giving rise to x(t); the correlation between $x(t_1)$ and $x(t_2)$ is $\exp[-\beta|t_1-t_2|]$. Fontaine and others (1984) also define q, the constant value of the spectral density function of the white noise which drives the Gauss-Markov x-process. The parameters, p, q, and β are related by

$$Var[x(t)] = p = q/(2\beta) \tag{10}$$

The variance of the observed residuals z(t) is

$$Var[z(t)] = p + r \tag{11}$$

where r is the variance of the measurement error v(t). The three parameters, p, β, and r, are computed by analyzing the statistical properties of the z(t) time series. These three site-specific parameters are needed to define this component of the uncertainty relationship. The Kalman filter utilizes these three parameters to determine the average relative variance of the errors of estimation of discharge as a function of the number of discharge measurements per year (Moss and Gilroy, 1980).

If the recorder at the primary site fails and there are no concurrent data at other sites that can be used to reconstruct the missing record at the primary site, there are at least two ways of estimating discharges at the primary site. A recession curve could be applied from the time of recorder stoppage until the gage was once again functioning, or the expected value of discharge for the period of missing data could be used as an estimate. The expected-value approach is used in this study to estimate V_e, the relative error variance during periods of no concurrent data at nearby stations. If the expected value is used to estimate discharge, the value that is used should be the expected value of discharge at the time of year of the missing record because of the seasonality of the streamflow processes. The variance of streamflow, which also is a seasonally varying parameter, is an estimate of the error variance that results from using the expected value as an estimate. Thus, the coefficient of variation squared (C_v) is an estimate of the required relative error variance V_e. Because C_v varies seasonally and the times of failures cannot be anticipated, a seasonally averaged value of C_v is used:

$$\bar{C}_v = \left[\frac{1}{365} \sum_{i=1}^{365} \left(\frac{\sigma_i}{\mu_i} \right)^2 \right]^{\frac{1}{2}} (100) \qquad (12)$$

where

σ_i is the standard deviation of daily discharges for the i^{th} day of the year,

μ_i is the expected value of discharge on the i^{th} day of the year, and

$(\bar{C}_v)^2$ is used as an estimate of V_e.

The variance, V_r, of the relative error during periods of reconstructed streamflow records is estimated on the basis of correlation between records at the primary site and records from other gaged nearby sites. The correlation coefficient, ρ_c, between the streamflows with seasonal trends removed at the site of interest and detrended streamflows at the other sites is a measure of the goodness of their linear relationship. The fraction of the variance of streamflow at the primary site that is explained by data from the other sites is equal to ρ_c^2. Thus, the relative error variance of flow estimates at the primary site obtained from secondary information will be

$$V_r = (1-\rho_c^2)\ \bar{C}_v^2 \qquad (13)$$

Sometimes the record for a gaging station can be reconstructed by correlation with more than one nearby gaging station. For the fraction of time when no secondary data are available from the gaging station typically used (secondary station) for record reconstruction (ε_e), data from another (tertiary) gaging station can be used. The correlation of data from the tertiary station with data from the station of interest is denoted R_2. The value of R_2 is always less than or equal to ρ_c. The variance of records estimated from a tertiary source of information is

$$(1 - R_2^2)\ (\bar{C}_v)^2 = (1 - R_2^2)\ V_e.$$

Because errors in streamflow estimates arise from three different sources with widely varying precisions, the resultant distribution of those errors may differ significantly from a normal or log-normal distribution. This lack of normality causes difficulty in interpretation of the resulting average estimation variance. When primary and secondary data are unavailable, the relative error variance V_e may be very large. This could yield correspondingly large values of $\bar{V}$ in equation (3) even if the probability that primary and secondary information are not available, ε_e, is quite small.

A new parameter, the equivalent Gaussian spread (EGS), is introduced here to assist in interpreting the results of the analyses. If it is assumed that the various errors arising from the three situations represented in equation (3) are log-normally distributed, the value of EGS was determined by the probability statement that

$$\text{Probability } [e^{-EGS} \leq (q_c(t) / q_T(t)) \leq e^{+EGS}] = 0.683 \qquad (14)$$

Thus, if the residuals $\ln q_c(t) - \ln q_T(t)$ were normally distributed, $(EGS)^2$ would be their variance. Here EGS is reported in units of percent because EGS is defined so that nearly two-thirds of the errors in instantaneous streamflow data will be within plus or minus EGS percent of the reported values.

The Application of K-CERA in the Hawaii District

As a result of the first two parts of this analysis, it has been suggested that all 124 of the currently existing stream gages in the Hawaii District program be continued in operation. These 124 stream gages were subjected to the K-CERA analysis with results that are described below.

Definition of Missing Record Probabilities

As described earlier, the statistical characteristics of missing stage or other correlative data for computation of streamflow records can be defined by a single parameter, the value of k in the truncated negative exponential probability distribution of times to failure of the equipment. In the representation of $f(\tau)$ as given in equation 4, the average time to failure is 1/k. The value of 1/k will vary from site to site depending upon the type of equipment at the site and upon its exposure to natural elements and vandalism. The value of 1/k can be changed by advances in the technology of data collection and recording. To estimate 1/k in the Hawaii District, a period of actual data collection of 7 years duration in which little change in technology occurred and in which stream gages were visited on a consistent pattern of frequency was used. Three estimates of 1/k were determined for different geographical areas of the District. During this 7-year period one estimate of 1/k (555 days), for stations in the State of Hawaii, was based on an average of 4 percent of the time a gage could be expected to be malfunctioning and 8 visits per year.

Another estimate of 1/k (370 days), for stations in American Samoa, was based on an average of 4 percent of the time a gage could be expected to be malfunctioning and 12 visits per year. The third estimate of 1/k (180 days), for stations in the Other Pacific Areas other than in American Samoa, was based on an average of 8 percent of the time a gage could be expected to be malfunctioning and 12 visits per year. The appropriate 1/k estimate for each geographical area was used to determine ε_f, ε_e, and ε_r, for each of the 124 stream gages as a function of the individual frequencies of visit.

Definition of Cross-Correlation Coefficient and Coefficient of Variation

To compute the values of V_e and V_r of the needed uncertainty functions, daily streamflow records for each of the 124 stations for the last 30 years or the part of the last 30 years for which daily streamflow values are stored in WATSTORE (Hutchinson, 1975) were retrieved. For each of the stream gages that had 3 or more complete water years of data, the value of C_v was computed and various options, based on combinations of other stream gages, were explored to determine the maximum ρ_c. For the three stations that had less than 3 water years of data, values of C_v and ρ_c were estimated subjectively.

The set of parameters for each station and the auxiliary records that gave the highest cross correlation coefficient are listed in table 4. A surprising fact from this step of the study is that two stations on Saipan correlate better, although the correlation is poor, with stations on Guam than they do with each other. This could be due just to chance.

Table 4.--Statistics of record reconstruction

Station no.	C_v	ρ_c	R_2	Source of reconstructed records		
010000	159	0.784	0.709	031000	108000	
019000	181	.895	.709	031000	108000	
031000	215	.856	.456	010000	019000	036000
036000	177	.941	.727	031000	049000	108000
049000	174	.915	.680	031000	036000	
060000	194	.930	.900	049000	063000	071000
061000	22.6	.632	.388	061200		
061200	23.3	.717	.700	061000	062000	063000
062000	172	.483	.096	061000	063000	100000
063000	134	.929	.868	069000	071000	
068000	117	.935	.900	060000	063000	080000
069000	89.3	.422	.366	063000	068000	071000
071000	136	.966	.904	060000	063000	068000
071500	110	.774	.700	068000	080000	089000
077000	88.6	.496	.168	079000	088000	
079000	114	.354	.192	069000	077000	080000
080000	205	.898	.800	068000	089000	
087000	181	.712	.700	088000	089000	091000
088000	127	.586	.486	087000	089000	091000
089000	172	.867	.800	068000	080000	097500
091000	135	.445	.340	077000	087000	088000
097500	105	.894	.800	080000	089000	103000
100000	64.6	.530	.500	062000	063000	103000
103000	123	.837	.800	036000	108000	
108000	113	.884	.800	036000	103000	
200000	159	.859	.756	212800	208000	345000
208000	160	.886	.772	200000	212800	345000
211600	174	.591	.475	213000	216000	345000
212800	197	.892	.799	200000	208000	345000
213000	137	.839	.671	208000	216000	345000
216000	231	.853	.779	226000	229000	229300
226000	263	.906	.811	216000	229000	229300
229000	172	.940	.820	226000	229300	240500
229300	166	.897	.766	229000	240500	
232000	144	.835	.756	229000	240500	
240500	104	.832	.752	226000	229000	229300
254000	123	.830	.638	229000	272200	240500
272200	80.1	.758	.587	229000	229300	254000
283600	49.0	.939	.294	283700	284200	294900
283700	37.7	.939	.312	283600	284200	294900

See footnote at end of table, p. 42.

Table 4.--Statistics of record reconstruction--Continued

Station no.	C_v	ρ_c	R_2	Source of reconstructed records		
284200	62.2	0.693	0.143	283600	283700	294900
294900	146	.834	.593	283600	284200	296500
296500	116	.804	.712	200000	208000	345000
302000	91.6	.407	.054	303000	325000	
303000	118	.765	.600	302000	325000	345000
304200	166	.808	.659	325000	345000	304200
325000	173	.921	.749	330000	345000	304200
330000	214	.907	.793	325000	345000	
345000	175	.880	.793	208000	325000	330000
400000	149	.698	.626	405500	408000	419500
404200	78.2	.746	.700	405500	408000	
405100	102	.959	.462	405300	405500	
405300	59.7	.959	.433	405100	405500	
405500	171	.870	.655	404200	408000	
408000	116	.901	.745	404200	405500	
414000	136	.685	.636	404200	405500	408000
419500	200	.724	.574	400000	404200	408000
501000	218	.688	.562	508000	518000	541500
508000	191	.970	.846	501000	518000	541500
512000	65.3	.947	.827	523000	538000	541000
518000	190	.967	.739	508000	541500	620000
523000	60.7	.985	.942	512000	541000	588000
531000	129	.729	.648	512000	538000	541000
538000	95.4	.864	.847	512000	523000	541000
541000	65.9	.984	.943	512000	523000	538000
541500	202	.882	.846	508000	518000	620000
587000	136	.802	.762	508000	518000	620000
588000	49.1	.896	.874	512000	523000	541000
589000	177	.826	.766	538000	541000	592000
592000	92.1	.789	.722	541000	588000	589000
594000	184	.760	.680	512000	538000	589000
599500	88.8	.788	.757	512000	523000	541000
618000	129	.839	.689	518000	541500	620000
620000	108	.880	.739	508000	518000	618000
638500	157	.539	.385	518000	587000	620000
700000	91.8	.825	.465	700900	713000	
700900	83.5	.796	.489	700000	713000	
700950*	80	.80	.50			
704000	188	.872	.727	713000	717000	
713000	131	.810	.727	704000	717000	

See footnote at end of table, p. 42.

Table 4.--Statistics of record reconstruction--Continued

Station no.	C_v	ρ_c	R_2	Source of reconstructed records		
717000	169	0.860	0.628	704000	713000	
720000	162	.945	.900	720300	756000	
720300	141	.936	.798	720000	725000	
720500	105	.796	.508	724800	726000	
724800	125	.867	.672	720000	720500	
725000	133	.916	.869	720000	758000	
726000	103	.763	.680	720000	720500	724800
727000	165	.590	.480	724800	726000	720500
756000	198	.924	.844	720000	725000	758000
758000	139	.939	.827	756000	759000	
759000	203	.921	.789	725000	756000	758000
764000	200	.420	.324	704000	717000	
800000	73.2	.214	.090	840000		
801000	165	.370	.342	848500	858000	
809600	132	.779	.645	848500	854500	
840000	179	.730	.617	809600	848100	
847000	140	.782	.686	848100	854500	
848100	139	.890	.645	847000	848500	
848500	122	.891	.676	847000	848100	
854500	77.8	.788	.617	809600	848100	
858000	185	.842	.700	840000	848500	
890600	86.0	.755	.578	890900	891400	
890900	97.2	.920	.700	890600	891400	
891310	72.8	.706	.660	890600	890900	
891400	110	.913	.666	890600	890900	
892000*	200	.85	.70			
892400	221	.867	.606	893100		
893100	216	.867	.660	892400		
893200	97.5	.660	.606	893100		
893400*	150	.70	.60			
893800	141	.261	.205	898600		
897600	112	.869	.824	893800	897900	
897900	118	.874	.817	897600	899620	
898600	107	.828	.817	897600		
899620	76.2	.830	.734	899750	899800	
899750	96.6	.906	.734	899620	899800	
899800	88.8	.930	.777	899620	899750	
912000	162	.888	.611	920500	948000	963900
920500	107	.887	.744	931000	933500	948000

See footnote at end of table, p. 42.

Table 4.--Statistics of record reconstruction--Continued

Station no.	C_v	ρ_c	R_2	Source of reconstructed records		
931000	149	0.853	0.671	920500	948000	
931500	83.5	.936	.744	931000	933500	
933500	85.2	.929	.593	920500	931000	931500
948000	175	.867	.593	912000	931000	
963900	161	.791	.568	912000	933500	948000

* Less than 3 water years of data are available. Estimates of C_v, ρ_c, and R_2 are subjective.

Kalman-Filter Definition of Variance

The determination of the variance V_f for each of the 124 stream gages required the execution of three distinct steps: (1) long-term rating analysis and computation of residuals of measured discharges from the long-term rating, (2) time-series analysis of the residuals to determine the input parameters of the Kalman-filter streamflow records, and (3) computation of the error variance, V_f, as a function of the time-series parameters, the discharge-measurement-error variance, and the frequency of discharge measurement.

The first step in the determination of the variance for a stream gage is the development of the long-term rating. An example of computing a long-term rating function determined for Kawaikoi was of the form:

$$LQM = B1 + B3 * LOG(GHT - B2) \qquad (5)$$

in which

LQM is the logarithmic (base e) value of the measured discharge,

GHT is the recorded gage height corresponding to the measured discharge,

B1 is the logarithm of discharge for a flow depth of 1 foot,

B2 is the gage height of zero flow, and

B3 is the slope of the rating curve.

The values of B1, B2, and B3 for this station were determined to be 2.09, 1.28, and 3.17, respectively.

A tabular presentation of the residuals of the measured discharges about the rating curve for Kawaikoi is given in table 5.

The time series of residuals, such as shown in table 5, is used to compute sample estimates of q and β, two of the three parameters required to compute V_f, by determining a best fit autocovariance function to the time series of residuals. Measurement variance, the third parameter, is determined from an assumed constant percentage standard error. For the Hawaii District program, measurements at stations in the State of Hawaii were assumed to have measurement errors ranging from 1 to 2 percent and the measurements at stations in the Other Pacific Areas were assumed to have measurement errors ranging from 1 to 5 percent depending on the measuring conditions at the station.

Table 5.--Residual data for Kawaikoi

Observation no.	Measurement no.	Date	Measured discharge (ft^3/s)	Measured discharge (log base e)	Residual (log base e)
1	368	Sept. 19, 1973	6.34	1.84688	0.04041
2	369	Oct. 18, 1973	41.3	3.72086	-0.01859
3	370	Dec. 14, 1973	16.4	2.79728	-0.00940
4	371	Jan. 23, 1974	14.6	2.68102	-0.07480
5	372	Mar. 1, 1974	7.89	2.06560	0.02578
6	373	May 2, 1974	14.5	2.67415	-0.00383
7	374	June 13, 1974	7.49	2.01357	0.00606
8	375	July 11, 1974	6.02	1.79509	-0.01138
9	376	Sept. 9, 1974	3.57	1.27257	-0.20617
10	377	Oct. 8, 1974	5.29	1.66582	0.11127
11	378	Dec. 11, 1974	9.87	2.28950	0.03236
12	379	Feb. 6, 1975	21.7	3.07731	0.02792
13	380	Mar. 12, 1975	17.5	2.86220	-0.01926
14	381	May 12, 1975	9.60	2.26176	0.09594
15	382	June 16, 1975	4.61	1.52823	0.16673
16	383	Aug. 13, 1975	2.81	1.03318	0.18957
17	384	Oct. 2, 1975	1.52	0.41871	0.08252
18	385	Nov. 12, 1975	9.60	2.26176	0.03477
19	386	Jan. 22, 1976	17.9	2.88480	0.12898
20	387	Mar. 15, 1976	19.7	2.98062	-0.02169
21	388	May 6, 1976	16.4	2.79728	0.01593
22	389	July 1, 1976	9.14	2.21266	0.14087
23	390	Aug. 16, 1976	6.48	1.86872	0.02785
24	391	Oct. 7, 1976	19.3	2.96011	0.02975
25	392	Dec. 13, 1976	5.33	1.67335	0.04476
26	393	Jan. 31, 1977	6.21	1.82616	0.01969
27	394	Mar. 10, 1977	17.0	2.83321	0.00141
28	395	Apr. 28, 1977	12.2	2.50144	0.06920
29	396	June 15, 1977	5.79	1.75613	-0.01555
30	397	Aug. 3, 1977	7.88	2.06433	-0.07046
31	398	Sept. 9, 1977	6.02	1.79509	0.05857
32	399	Oct. 18, 1977	2.18	0.77932	-0.20191
33	400	Dec. 12, 1977	5.79	1.75613	0.01962
34	401	Jan. 30, 1978	5.22	1.65250	0.06071
35	402	Mar. 13, 1978	2.87	1.05431	-0.01546
36	403	May 8, 1978	12.4	2.51770	-0.02612
37	404	June 9, 1978	26.6	3.28091	0.02793
38	405	July 26, 1978	8.64	2.15640	0.02162
39	406	Sept. 8, 1978	7.67	2.03732	-0.00250
40	407	Oct. 17, 1978	2.80	1.02962	0.00381
41	408	Dec. 12, 1978	34.0	3.52636	0.04111
42	409	Feb. 9, 1979	27.6	3.31782	0.10896
43	410	Apr. 6, 1979	14.1	2.64617	-0.03180
44	411	May 11, 1979	10.6	2.36085	-0.04287
45	412	June 20, 1979	34.6	3.54385	-0.00190
46	413	Aug. 8, 1979	4.49	1.50185	-0.16313
47	414	Sept. 19, 1979	2.12	0.75142	0.00299

Table 5.--Residual data for Kawaikoi--Continued

Observation no.	Measurement no.	Date	Measured discharge (ft^3/s)	Measured discharge (log base e)	Residual (log base e)
48	415	Oct. 17, 1979	3.14	1.14422	-0.05388
49	416	Dec. 17, 1979	23.4	3.15274	0.05696
50	417	Jan. 30, 1980	42.2	3.74242	0.02182
51	418	Mar. 7, 1980	31.8	3.45947	0.05672
52	419	Apr. 29, 1980	28.0	3.33220	0.07923
53	420	June 10, 1980	59.7	4.08933	-0.00523
54	421	July 28, 1980	11.4	2.43361	0.00137
55	422	Sept. 11, 1980	5.04	1.61741	-0.04757
56	423	Oct. 14, 1980	14.4	2.66723	-0.01075
57	424	Dec. 10, 1980	8.18	2.10169	-0.09486
58	425	Jan. 28, 1981	17.3	2.85071	-0.05530
59	426	Mar. 11, 1981	32.5	3.48124	-0.00401
60	427	Apr. 22, 1981	10.4	2.34181	-0.09043
61	428	June 12, 1981	11.0	2.39790	-0.14592
62	429	July 23, 1981	12.5	2.52573	-0.12586
63	430	Sept. 14, 1981	13.7	2.61740	-0.08674
64	431	Oct. 15, 1981	6.46	1.86563	-0.10925
65	432	Dec. 7, 1981	1030	6.93731	-0.10691
66	433	Jan. 27, 1982	74.9	4.31615	0.05793
67	434	Mar. 15, 1982	31.7	3.45632	-0.00851
68	435	Apr. 22, 1982	114	4.73620	0.17403
69	436	June 3, 1982	6.81	1.98139	-0.15340
70	437	July 21, 1982	22.4	3.10906	-0.05504
71	438	Sept. 9, 1982	6.34	1.84688	-0.02803
72	439	Oct. 14, 1982	7.95	2.07317	0.03336

As discussed earlier, q and β can be expressed as the process variance of the shifts from the rating curve and the 1-day autocorrelation coefficient of these shifts. Table 6 presents a summary of the autocovariance analysis expressed in terms of process variance and 1-day autocorrelation for all stations in the District.

The autocovariance parameters, summarized in table 6, and data from the definition of missing record probabilities, summarized in table 4, are used jointly to define uncertainty functions for each gaging station. The uncertainty functions give the relationship of total error variance to the number of visits and discharge measurements. An example of an uncertainty function is given in figure 4. This function is based on the assumption that a measurement was made during each visit to the station.

Stations 303000 and 899620 were assigned zero uncertainty because it was assumed that the residual time series was not an auto-regressive process at these stations. They were not included in the average standard error calculations.

In the Hawaii District, feasible routes to service the 124 stream gages were determined after consultation with personnel in the Hydrologic Data Section of the Hawaii District office and after review of the uncertainty functions. The gaging stations were divided into two groups. One group is for the State of Hawaii stations and the second the Other Pacific Areas. In summary, 92 routes were selected to service all the stream gages in the State of Hawaii. Forty-one routes were selected for the Other Pacific Areas. These routes included all possible combinations that describe the current operating practice, alternatives that were under consideration as future possibilities, routes that visited certain key individual stations, and combinations that grouped proximate gages where the levels of uncertainty indicated more frequent visits might be useful. These routes and the stations visited on each are summarized in tables 7 and 8.

The costs associated with the practical routes must be determined. Fixed costs to operate a gage typically include equipment rental, batteries, electricity, data processing and storage, computer charges, maintenance, miscellaneous supplies, and analysis and supervisory charges. For the Hawaii District, average values were applied to each station in the program for all the above categories.

Table 6.--Summary of the autocovariance analysis

Station no.	Abbreviated station name	RHO*	Measurement variance (log base e)^2	Process variance (log base e)^2	Length of period (days)
STATE OF HAWAII					
010000	Kawaikoi	0.617	0.0004	0.0039	365
019000	Waialae	.992	.0004	.0577	365
031000	Waimea	.984	.0004	.0591	365
036000	Makaweli	.994	.0004	.1512	365
049000	Hanapepe	.446	.0004	.1240	365
060000	South Wailua	.984	.0004	.0111	365
061000	Ditch Lihue	.986	.0004	.0032	365
061200	Ditch Waikoko	.964	.0004	.0007	365
062000	Stable	.882	.0004	.0677	365
063000	North Wailua Lihue	.959	.0004	.0175	365
068000	East Wailua	.982	.0004	.0129	365
069000	Wailua Ditch	.868	.0004	.0024	365
071000	North Wailua Kapaa	.960	.0004	.0093	365
071500	Opaekaa	.987	.0004	.0028	365
077000	Makaleha	.570	.0004	.0014	365
079000	Kapahi (Ditch nr Kealia)	.922	.0004	.0020	365
080000	Kapaa	.973	.0004	.0334	365
087000	Anahola Wasteway	.449	.0004	.1055	365
088000	Anahola Keneha	.963	.0004	.0016	365
089000	Anahola	.960	.0004	.0514	365
091000	Lower Anahola	.985	.0004	.3501	365
097500	Halaulai	.568	.0004	.0050	365
100000	Tunnel outlet	.668	.0004	.0001	365
103000	Hanalei	.992	.0004	.0159	365
108000	Wainiha	.996	.0004	.0096	365
200000	North Kaukonahua	.963	.0004	.0019	365
208000	South Kaukonahua	.950	.0004	.0020	365
211600	Makaha	.963	.0004	.0098	365
212800	Kipapa	.986	.0004	.1474	365
213000	Waikele	.960	.0004	.0116	365
216000	Wahiawa	.937	.0004	.0173	365
226000	North Halawa	.973	.0004	.0266	365
229000	Kalihi Honolulu	.870	.0004	.0047	365
229300	Kalihi Kalihi	.519	.0004	.0088	365
232000	Nuuanu	.974	.0004	.0084	365
240500	Waiakeakua	.985	.0004	.0072	365
254000	Makawao	.635	.0004	.0023	365
272200	Kamooalii	.974	.0004	.0031	365
283600	South Waihee	.829	.0004	.0062	365
283700	North Waihee	.986	.0004	.0088	365
284200	Waihee	.657	.0004	.0026	365
294900	Waikane	.961	.0004	.0036	365
296500	Kahana	.978	.0004	.0032	365
302000	Punaluu Ditch	.973	.0004	.0242	365

See footnote at end of table, p. 49.

Table 6.--Summary of the autocovariance analysis--Continued

Station no.	Abbreviated station name	RHO*	Measurement variance (log base e)^2	Process variance (log base e)^2	Length of period (days)
304200	Kaluanui	0.601	0.0004	0.0081	365
325000	Kamananui Pupukea	.993	.0004	.1573	365
345000	Opaeula	.980	.0004	.0062	365
400000	Halawa	.985	.0004	.0268	365
404200	Pilipililau	.400	.0004	.0026	365
405100	Tunnel east	.982	.0004	.0031	365
405300	Tunnel west	.709	.0004	.0007	365
405500	Waikolu	.995	.0004	.0790	365
408000	Waikolu pipeline	.994	.0004	.0654	365
414000	Kaunakakai	.661	.0004	.1737	365
419500	Papio	.997	.0004	.1735	365
501000	Palikea	.817	.0004	.0160	365
508000	Hanawi	.966	.0004	.0048	365
512000	Koolau Nahiku	.764	.0001	.0002	365
518000	Wailuaiki	.991	.0004	.0054	365
523000	Koolau Keanae	.964	.0004	.0026	365
531000	Kula	.503	.0004	.0360	365
538000	Spreckels	.709	.0004	.0016	365
541000	Koolau Haipuaena	.981	.0004	.0001	365
541500	Manuel	.974	.0004	.0030	365
587000	Honopou	.969	.0004	.0030	365
588000	Wailoa	.979	.0004	.0007	365
589000	Hamakua Honopou	.656	.0004	.0039	365
592000	Lowrie	.891	.0004	.0016	365
594000	Haiku	.711	.0004	.0054	365
599950	Opana	.973	.0004	.0017	365
618000	Kahakuloa	.989	.0004	.0025	365
620000	Honokohau	.986	.0004	.0011	365
638500	Kahoma	.985	.0004	1.043	365
700000	Waiakea	.950	.0004	.0002	365
700900	Olaa	.991	.0004	.0047	365
700950	Lyman	.950	.0004	.0030	365
704000	Wailuku Piihonua	.960	.0004	.0044	365
713000	Wailuku Hilo	.977	.0004	.0048	365
717000	Honolii	.969	.0004	.0001	365
720000	Kawainui	.985	.0004	.0034	365
720300	Kawaiki	.990	.0004	.0019	365
720500	Hamakua Kawaiki	.635	.0004	.0039	365
724800	Hamakua Alakahi	.950	.0004	.0057	365
725000	Alakahi	.664	.0004	.0043	365
726000	Hamakua Waimea	.937	.0004	.0030	365
727000	Hamakua Puukapu	.950	.0004	.0030	365
756000	Kohakohau	.714	.0004	.0007	365
758000	Waikoloa	.424	.0004	.0002	365
759000	Hauani	.587	.0004	.0022	365
764000	Hilea	.715	.0004	.0011	365

See footnote at end of table, p. 49.

Table 6.--Summary of the autocovariance analysis--Continued

Station no.	Abbreviated station name	RHO*	Measurement variance (log base e)^2	Process variance (log base e)^2	Length of period (days)
OTHER PACIFIC AREAS					
800000	Denni	0.940	0.0025	0.0590	365
801000	Talofofo	.961	.0025	.2170	365
809600	La Sa Fua	.954	.0025	.0466	365
840000	Tinaga	.923	.0016	.0451	365
847000	Imong	.867	.0025	.0462	365
848100	Almagosa	.928	.0025	.0195	365
848500	Maulap	.982	.0025	.0151	365
854500	Ugum	.979	.0025	.0042	365
858000	Ylig	.827	.0025	.0240	365
890600	Diongradid	.995	.0025	.0061	365
890900	Tabecheding	.965	.0001	.0022	365
891400	Ngerdorch	.979	.0025	.0074	365
891310	Kmekumel	.937	.0004	.0041	365
892000	Qatliw	.950 1/	.0025	.0250	365
892400	Qaringeel	.912	.0025	.0555	365
893100	Burong	.939	.0004	.0267	365
893200	Mukong	.939	.0025	.1607	365
893400	Eyeb	.916	.0025	.1770	365
893800	Wichen	.950 1/	.0025	.0371	365
897600	Nanpil	.973	.0025	.0390	365
897900	Lewi	.934	.0025	.0346	365
898600	Luhpwor	.331	.0025	.0044	365
899750	Malem	.986	.0025	.0624	365
899800	Tofol	.912	.0025	.0079	365
912000	Pago	.901	.0004	.0128	365
920500	Aasu	.954	.0004	.0119	365
931000	Ataulomа	.977	.0004	.1156	365
931500	Asili	.746	.0004	.0169	365
933500	Leafu Leone	.930	.0004	.0121	365
948000	Afuelo	.801	.0004	.0590	365
963900	Leafu Auasi	.985	.0004	.1669	365

* One-day autocorrelation coefficient.

1/ Estimate.

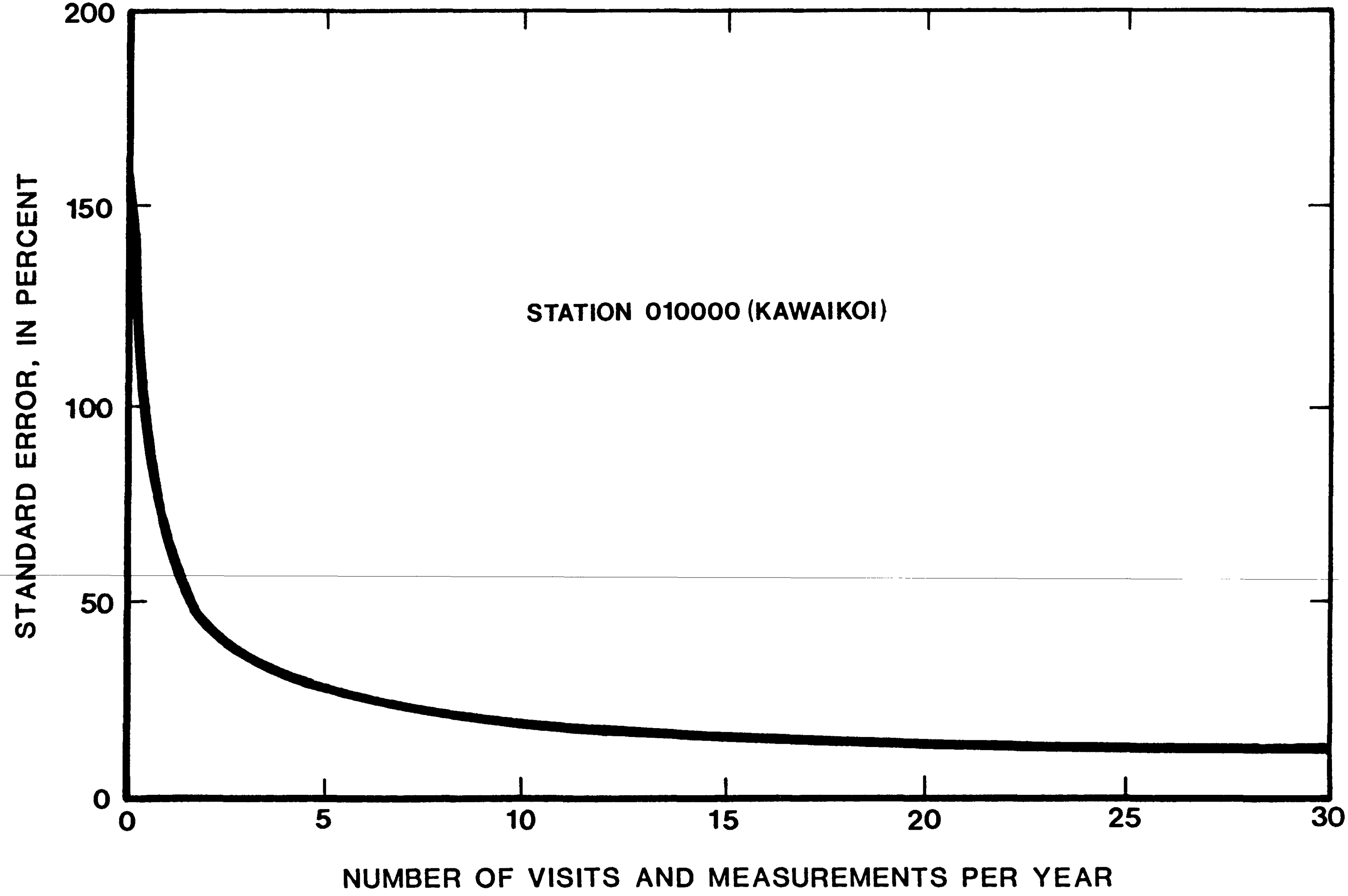

Figure 4. Typical uncertainty function for instantaneous discharge.

Table 7.--Summary of the routes that may be used to visit stations in the State of Hawaii

Route no.	Stations serviced on the route			
1	010000			
2	019000	108000		
3	031000			
4	036000	049000		
5	060000	063000		
6	061000	100000		
7	061200	062000	069000	
8	068000			
9	071000			
10	071500			
11	077000	079000	088000	
12	080000	087000	089000	091000
13	097500			
14	103000			
15	010000	031000		
16	060000	061000	061200	
17	062000	063000	068000	
18	069000	077000	079000	
19	071000	071500		
20	080000			
21	087000	088000		
22	089000	091000		
23	097500	103000		
24	100000			
25	200000			
26	208000			
27	211600			
28	212800			
29	213000	216000		
30	226000			
31	229000			
32	229300	232000		
33	240500			
34	254000			
35	272200			
36	283600	283700	284200	
37	294900	296500		
38	302000	303000	304200	
39	330000			
40	345000			
41	325000			
42	216000			
43	304200			
44	200000	208000		
45	211600	213000	216000	
46	212800	226000		
47	212800	345000		

Table 7.--Summary of the routes that may be used to visit stations in the State of Hawaii--Continued

Route no.	Stations serviced on the route							
48	226000	229300	232000					
49	325000	330000						
50	232000	254000	272200					
51	325000	330000	345000					
52	400000							
53	419500							
54	405100	405300	405500	408000				
55	414000							
56	404200							
57	400000	419500						
58	414000	419500						
59	405100	405300	405500	408000	414000	419500		
60	501000							
61	508000	541500						
62	512000	518000	523000					
63	531000	599500						
64	538000	541000						
65	587000							
66	588000	589000						
67	592000	594000						
68	618000							
69	620000							
70	638500							
71	531000							
72	541500							
73	589000							
74	594000							
75	620000	638500						
76	508000	531000						
77	538000	541000	541500					
78	501000	508000	512000	518000	523000	541500		
79	700000							
80	700900							
81	700950							
82	704000							
83	713000							
84	717000							
85	720000	720300	720500	724800	725000			
86	726000	727000	756000	758000	759000			
87	764000							
88	727000							
89	700900	700950						
90	700900	700950	704000					
91	713000	717000						
92	720000	720300	720500	724800	725000	726000	727000	756000

Table 8.--Summary of the routes that may be used to visit stations in the Other Pacific Areas

Route no.	Stations serviced on the route		
1	800000	801000	
2	809600	858000	
3	840000	854500	
4	847000	848100	848500
5	890600		
6	890900		
7	891310		
8	891400		
9	892000	892400	
10	893100	893200	893400
11	893800		
12	897600	897900	
13	898600		
14	899620		
15	899750	899800	
16	912000	948000	
17	920500		
18	931000	931500	933500
19	963900		
20	800000		
21	801000		
22	809600		
23	840000		
24	847000		
25	848100		
26	848500		
27	858000		
28	809600	840000	858000
29	892000		
30	892400		
31	893100		
32	893200		
33	893400		
34	897600		
35	897900		
36	899750		
37	912000		
38	912000	963900	
39	931000		
40	948000		
41	920500	948000	

Visit costs are those associated with paying the hydrographer for the time actually spent at a station servicing the equipment and making a discharge measurement. These costs vary from station to station and are a function of the difficulty and time required to make the discharge measurement. Average visit times were calculated for each station based on an analysis of discharge measurement data available. This time was then multiplied by the average hourly salary of hydrographers in the respective field offices of the Hawaii District to determine total visit costs.

Route costs include the vehicle cost associated with driving the number of miles it takes to cover the route, the cost of the hydrographer's time while in transit, and any per diem associated with the time it takes to complete the trip.

K-CERA Results

The "Traveling Hydrographer Program" utilizes the uncertainty functions along with the appropriate cost data and route definitions to compute the most cost-effective way of operating the stream-gaging program. In this application, the first step was to simulate the current practice and determine the total uncertainty associated with it. To accomplish this, the number of visits being made to each stream gage and the specific routes that are being used to make these visits were fixed. Current practice for the Hawaii District calls for discharge measurements to be made 100 percent of the time that a station is visited, except when there is no flow in the stream. For stations where no flow was observed, past measurement record was examined to determine the probability of making a measurement at each such site and adjustments were applied. The resulting average error of estimation for the current practice in the State of Hawaii and the Other Pacific Areas is plotted as a point in figures 5 and 6 and is 21.0 percent and 25.9 percent, respectively.

The line labeled 'with lost record' on figures 5 and 6 represents the minimum level of average uncertainty that can be obtained for a given budget with the existing instrumentation and technology. The line was defined by several runs of the "Traveling Hydrographer Program" with different budgets. Constraints on the operations other than budget were defined as described below.

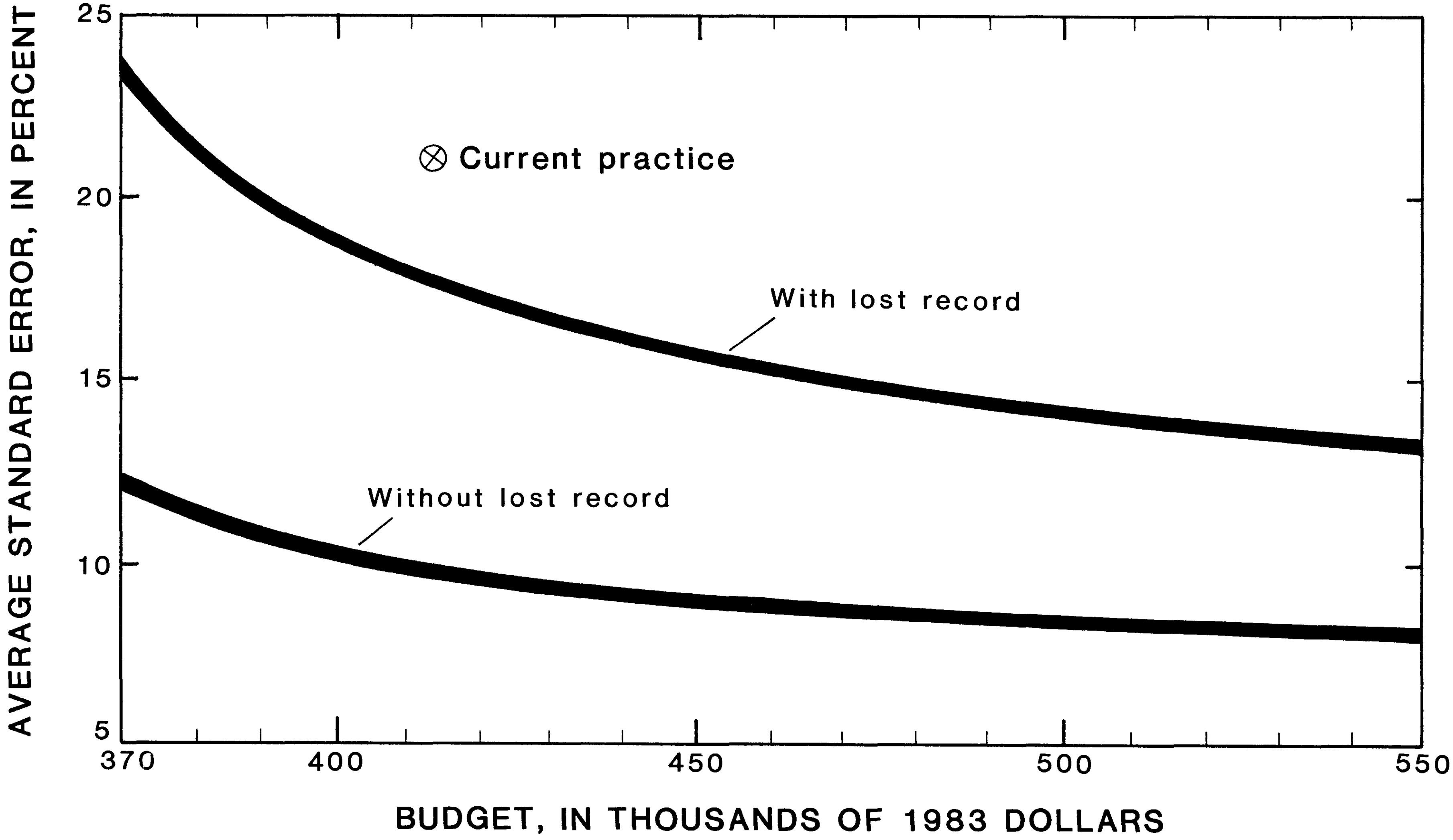

Figure 5. Temporal average standard error per stream gage for the State of Hawaii.

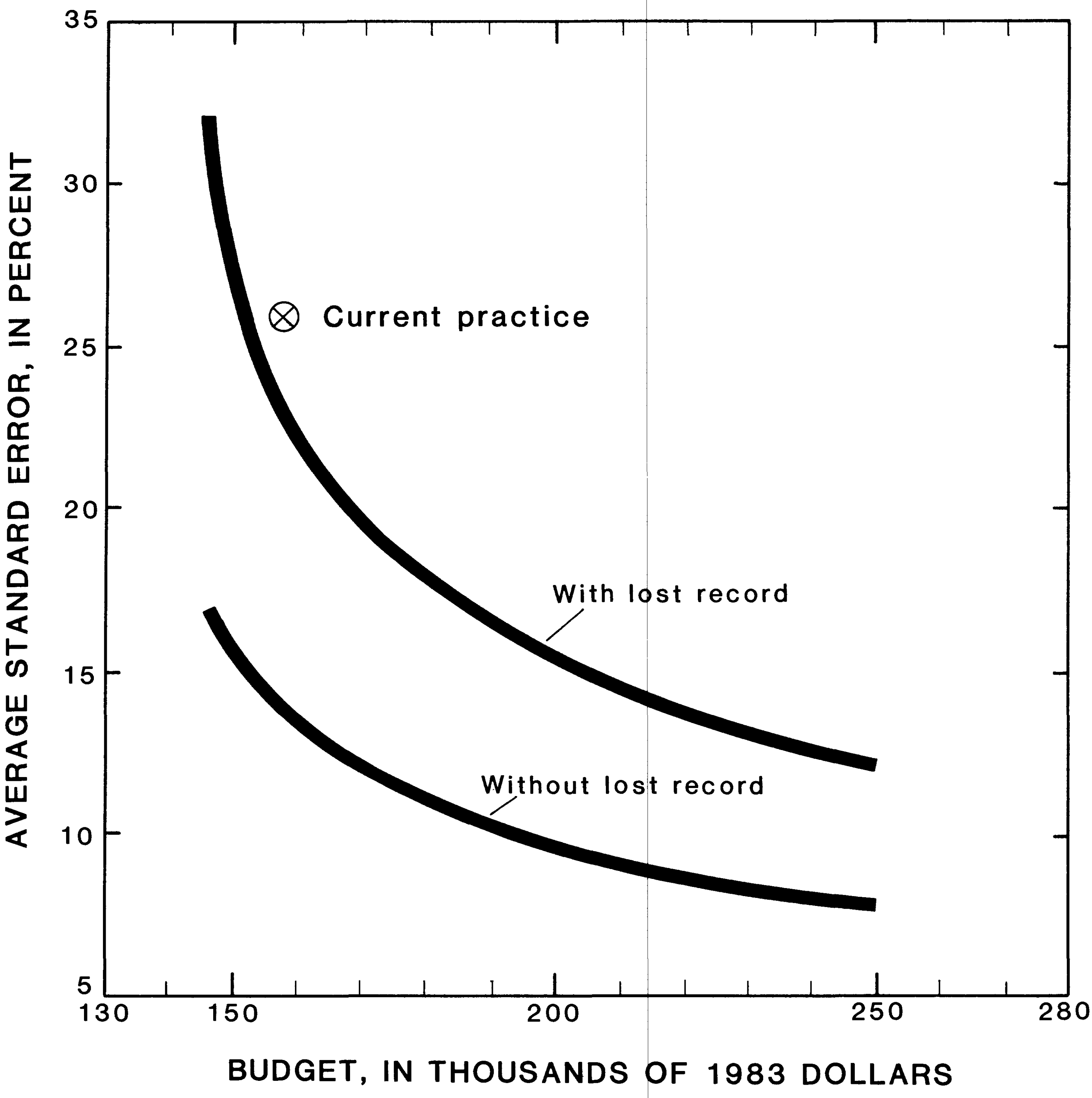

Figure 6. Temporal average standard error per stream gage for the Other Pacific Areas.

To determine the minimum number of times each station must be visited, consideration was given to the physical limitations of the method used to record data. The effect of visitation frequency on the accuracy of the data and amount of lost record is taken into account in the uncertainty analysis. In the Hawaii District, a minimum requirement of four visits per year was calculated and applied to most stations. This value was based on limitations of the batteries used to drive recording equipment, and the capacities of the uptake spools on the digital recorders.

Minimum visit requirements should also reflect the need to visit stations for special reasons such as water-quality sampling. In the Hawaii District, water-quality work for the benchmark and NASQAN stations do influence minimum visit requirements.

The results in figures 5 and 6, and tables 9 and 10 summarize the K-CERA analysis. It should be emphasized that figures 5 and 6, and tables 9 and 10 are based on various assumptions (stated previously) concerning both the time series of shifts to the stage-discharge relationship and the methods of record reconstruction. Where a choice of assumptions was available, the assumption that would not underestimate the magnitude of the error variances was chosen.

It can be seen that the current policy results in an average standard error of estimate of streamflow of 21.0 percent for the State of Hawaii and 25.9 percent for the Other Pacific Areas. This policy requires a budget of $413,370 and $157,250 to operate the 92- and 32-station stream-gaging programs for the respective groups. The range in standard errors for the stations in the State of Hawaii is from a low of 2.8 percent for station 541000 (Koolau Haipuena) to a high of 78.5 percent at station 638500 (Kahoma). The similar figures for the Other Pacific Areas range from a low of 9.9 percent at station 899800 (Tofol) to a high of 52 percent at station 801000 (Talofofo). It is possible to obtain the same average standard errors of 21.0 percent and 25.9 percent with a reduced budget of about $381,000 and $151,000, respectively, with a change of policy in the field activities of the stream-gaging program.

It would be possible to reduce the average standard error for the State of Hawaii by a policy change while maintaining the same budget of $413,370. In this case, the average standard error would decrease from 21.0 to 17.7 percent. Extremes of standard error for individual sites would be 3.1 and 47.2 percent for stations 061200 (Ditch Waikoko) and 414000 (Kaunakakai), respectively.

Table 9.--Selected results of K-CERA analysis for the State of Hawaii

Station no. and name	Current operation cost	Budget, in thousands of 1983 dollars					
	413.4	370	400	413.4	450	500	550
	Standard error (SE) of instantaneous discharge, in percent [Equivalent Gaussian spread (EGS)] (Number of visits per year to site)						
Average SE per station for the State of Hawaii[1/]	21.0	23.7	18.8	17.7	15.6	14.0	12.9
EGS for the State of Hawaii	[6.2]	[7.3]	[6.3]	[6.0]	[5.4]	[4.9]	[4.5]
010000 Kawaikoi	20.6 [6.45] (8)	28.2 [6.90] (4)	20.6 [6.45] (8)	17.9 [6.30] (11)	15.7 [6.16] (15)	13.6 [6.00] (21)	12.9 [5.92] (24)
019000 Waialae	22.9 [12.0] (5)	25.4 [13.5] (4)	25.4 [13.5] (4)	25.4 [13.5] (4)	22.9 [12.0] (5)	21.0 [10.8] (6)	18.3 [9.26] (8)
031000 Waimea	29.0 [15.1] (6)	29.0 [15.1] (6)	24.0 [12.4] (9)	21.8 [11.1] (11)	18.7 [9.47] (15)	15.8 [7.94] (21)	14.5 [7.24] (25)
036000 Makaweli	16.0 [12.0] (9)	23.6 [18.8] (4)	18.1 [13.8] (7)	17.0 [12.8] (8)	13.9 [10.3] (12)	11.4 [8.28] (18)	9.67 [6.98] (25)
049000 Hanapepe	37.5 [36.5] (9)	39.8 [37.8] (4)	38.1 [36.9] (7)	37.8 [36.7] (8)	36.9 [36.2] (12)	36.1 [35.6] (18)	35.4 [35.0] (25)
060000 South Wailua	12.5 [4.67] (12)	21.1 [7.97] (4)	16.2 [6.11] (7)	16.2 [6.11] (7)	13.1 [4.87] (11)	11.6 [4.31] (14)	10.6 [3.91] (17)
061000 Ditch Lihue	3.67 [2.40] (12)	6.03 [4.01] (4)	6.03 [4.01] (4)	6.03 [4.01] (4)	6.03 [4.01] (4)	5.48 [3.64] (5)	5.06 [3.35] (6)
061200 Ditch Waikoko	3.11 [1.67] (12)	4.55 [2.26] (5)	3.23 [1.73] (11)	3.11 [1.67] (12)	2.72 [1.49] (16)	2.40 [1.33] (21)	2.17 [1.21] (26)

See footnote at end of table, p. 67.

Table 9.--Selected results of K-CERA analysis for the State of Hawaii--Continued

Station no. and name	Current operation cost	Budget, in thousands of 1983 dollars					
	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)						
	413.4	370	400	413.4	450	500	550
062000 Stable	33.4 [23.5] (12)	45.2 [27.5] (5)	32.5 [23.1] (13)	29.6 [21.7] (17)	25.2 [19.2] (26)	21.6 [16.7] (38)	19.4 [15.1] (48)
063000 North Wailua Lihue	11.7 [8.83] (12)	17.7 [12.5] (4)	13.2 [9.84] (9)	11.7 [8.83] (12)	9.13 [6.90] (21)	7.57 [5.71] (31)	6.77 [5.10] (39)
068000 East Wailua	8.48 [5.29] (12)	8.48 [5.30] (12)	8.48 [5.29] (12)	8.48 [5.29] (12)	8.48 [5.29] (12)	7.17 [4.45] (17)	6.31 [3.89] (22)
069000 Wailua Ditch	14.0 [4.59] (12)	20.8 [5.17] (5)	14.5 [4.65] (11)	14.0 [4.59] (12)	12.3 [4.37] (16)	10.6 [4.07] (22)	9.20 [3.73] (30)
071000 Wailua Kapaa	10.1 [7.42] (8)	13.0 [9.03] (4)	12.0 [8.54] (5)	10.6 [7.75] (7)	9.24 [6.85] (10)	8.01 [5.98] (14)	7.34 [5.48] (17)
071500 Opaekaa	14.2 [2.68] (8)	19.7 [3.77] (4)	16.3 [3.09] (6)	15.1 [2.86] (7)	12.7 [2.40] (10)	10.8 [2.03] (14)	9.79 [1.85] (17)
077000 Makaleha	13.1 [3.84] (12)	19.7 [4.64] (5)	14.3 [3.88] (10)	12.7 [3.81] (13)	11.0 [3.73] (18)	9.83 [3.66] (23)	9.02 [3.60] (28)
079000 Kapahi	17.8 [3.66] (12)	27.0 [4.42] (5)	19.5 [3.85] (10)	17.2 [3.57] (13)	14.7 [3.23] (18)	13.0 [2.97] (23)	11.8 [2.74] (28)
080000 Kapaa	20.2 [14.4] (12)	26.0 [17.1] (6)	18.5 [13.3] (15)	17.1 [12.5] (18)	13.9 [10.2] (29)	11.8 [8.68] (41)	10.4 [7.66] (53)
087000 Anahola wasteway	38.4 [33.5] (12)	42.1 [34.5] (7)	36.8 [33.1] (16)	36.0 [32.8] (19)	34.0 [31.9] (30)	32.1 [30.7] (47)	30.5 [29.4] (66)

See footnote at end of table, p. 67.

Table 9.--Selected results of K-CERA analysis for the State of Hawaii--Continued

Station no. and name	Current operation cost	Budget, in thousands of 1983 dollars					
	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)						
	413.4	370	400	413.4	450	500	550
088000 Anahola Kaneha	17.1 [2.59] (12)	23.9 [3.34] (6)	17.8 [2.67] (11)	15.8 [2.43] (14)	13.6 [2.14] (19)	11.3 [1.79] (28)	9.80 [1.57] (37)
089000 Anahola	20.1 [15.0] (12)	23.7 [17.5] (8)	16.3 [12.2] (19)	14.9 [11.2] (23)	13.1 [9.79] (30)	11.2 [8.35] (41)	9.89 [7.32] (53)
091000 Lower Anahola	32.2 [26.5] (12)	39.2 [32.8] (8)	25.6 [20.7] (19)	23.3 [18.7] (23)	20.3 [16.2] (30)	17.3 [13.8] (41)	15.2 [12.0] (21)
097500 Halaulani	11.6 [7.26] (8)	14.8 [7.70] (4)	13.6 [7.53] (5)	12.8 [7.42] (6)	11.6 [7.26] (8)	10.5 [7.11] (11)	9.83 [7.00] (14)
100000 Tunnel outlet	9.03 [.94] (12)	15.3 [1.05] (4)	15.3 [1.05] (4)	15.3 [1.05] (4)	13.8 [1.02] (5)	11.7 [.99] (7)	10.4 [.97] (9)
103000 Hanalei	14.2 [4.93] (8)	19.8 [7.19] (4)	17.8 [6.36] (5)	16.3 [5.77] (6)	14.2 [4.93] (8)	12.2 [4.15] (11)	10.8 [3.66] (14)
108000 Wainiha	13.6 [3.57] (5)	15.2 [4.07] (4)	15.2 [4.07] (4)	15.2 [4.07] (4)	13.6 [3.57] (5)	12.5 [3.21] (6)	10.9 [2.77] (8)
200000 North Kaukonahua	16.6 [3.33] (8)	23.0 [4.17] (4)	17.7 [3.49] (7)	16.6 [3.33] (8)	13.6 [2.85] (12)	12.2 [2.60] (15)	10.6 [2.29] (20)
208000 South Kaukonahua	15.2 [3.72] (8)	21.1 [4.46] (4)	16.2 [3.86] (7)	15.2 [3.72] (8)	12.6 [3.25] (12)	11.3 [2.98] (15)	9.81 [2.66] (20)
211600 Makaha	28.9 [7.51] (8)	36.1 [8.80] (5)	23.8 [6.39] (12)	22.1 [5.98] (14)	18.1 [4.96] (21)	15.5 [4.24] (29)	13.9 [3.81] (36)

See footnote at end of table, p. 67.

Table 9.--Selected results of K-CERA analysis for the State of Hawaii--Continued

Station no. and name	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)						
	Current operation cost	Budget, in thousands of 1983 dollars					
	413.4	370	400	413.4	450	500	550
212800 Kipapa	25.4 [19.4] (8)	31.5 [24.5] (5)	21.8 [16.4] (11)	19.4 [14.4] (14)	16.7 [12.3] (19)	14.2 [10.4] (26)	12.8 [9.32] (32)
213000 Waikele	15.2 [7.69] (10)	19.1 [9.16] (6)	14.0 [7.15] (12)	12.6 [6.51] (15)	10.8 [5.57] (21)	9.19 [4.78] (29)	8.26 [4.29] (36)
216000 Waiawa	23.9 [10.8] (10)	29.9 [12.3] (6)	22.0 [10.2] (12)	19.9 [9.46] (15)	17.0 [8.29] (21)	14.6 [7.19] (29)	13.2 [6.51] (36)
226000 North Halawa	24.9 [12.0] (8)	30.6 [14.1] (5)	21.5 [10.5] (11)	19.2 [9.41] (14)	16.6 [8.14] (19)	14.2 [6.96] (26)	12.8 [6.27] (32)
229000 Kalihi Honolulu	11.3 [6.23] (12)	11.3 [6.23] (12)	11.3 [6.23] (12)	11.3 [6.23] (12)	11.3 [6.23] (12)	10.1 [5.90] (16)	9.25 [5.60] (20)
229300 Kalihi Kalihi	17.2 [9.72] (8)	22.4 [10.3] (4)	17.2 [9.72] (8)	16.6 [9.64] (9)	15.1 [9.47] (12)	13.5 [9.28] (17)	12.6 [9.12] (22)
232000 Nuuanu	16.8 [6.14] (8)	16.8 [6.14] (8)	13.4 [4.91] (13)	12.9 [4.75] (14)	10.3 [3.80] (22)	8.86 [3.26] (30)	7.69 [2.83] (40)
240500 Waiakeakua	12.3 [4.50] (8)	17.0 [6.27] (4)	13.1 [4.82] (7)	12.3 [4.50] (8)	10.5 [3.83] (11)	9.05 [3.28] (15)	8.06 [2.92] (19)
254000 Makawao	14.5 [4.94] (8)	19.7 [5.29] (4)	14.5 [4.94] (8)	13.1 [4.86] (10)	11.7 [4.76] (13)	10.3 [4.64] (18)	9.45 [4.56] (22)
272200 Kamooalii	11.0 [3.75] (8)	12.6 [4.22] (6)	12.6 [4.22] (6)	11.7 [3.96] (7)	9.90 [3.40] (10)	8.42 [2.92] (14)	7.45 [2.60] (18)

See footnote at end of table, p. 67.

Table 9.--Selected results of K-CERA analysis for the State of Hawaii--Continued

Station no. and name	Current operation cost 413.4	Budget, in thousands of 1983 dollars 370	400	413.4	450	500	550
	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)						
283600 South Waihee	7.84 [7.52] (10)	8.11 [7.74] (8)	8.11 [7.74] (8)	8.11 [7.74] (8)	8.11 [7.74] (8)	7.84 [7.52] (10)	7.62 [7.34] (12)
283700 North Waihee	4.71 [4.29] (10)	5.24 [4.81] (8)	5.24 [4.81] (8)	5.24 [4.81] (8)	5.24 [4.81] (8)	4.71 [4.29] (10)	4.31 [3.90] (12)
284200 Waihee	9.47 [5.30] (10)	10.3 [5.50] (8)	10.3 [5.50] (8)	10.3 [5.50] (8)	10.3 [5.50] (8)	9.47 [5.30] (10)	8.85 [5.17] (12)
294900 Waikane	16.7 [4.63] (8)	23.0 [5.75] (4)	16.7 [4.63] (8)	15.8 [4.44] (9)	13.7 [3.97] (12)	11.3 [3.34] (18)	10.5 [3.11] (21)
296500 Kahana	14.2 [3.57] (8)	19.7 [4.78] (4)	14.2 [3.57] (8)	13.4 [3.38] (9)	11.7 [2.97] (12)	9.56 [2.44] (18)	8.86 [2.26] (21)
302000 Punaluu Ditch	19.9 [11.5] (8)	26.7 [14.8] (4)	18.9 [11.0] (9)	17.2 [10.1] (11)	14.9 [8.74] (15)	12.7 [7.40] (21)	11.4 [6.66] (26)
304200 Kaluanui	21.4 [9.30] (8)	28.6 [9.91] (4)	20.4 [9.22] (9)	18.8 [9.09] (11)	16.7 [8.89] (15)	14.8 [8.67] (21)	13.8 [8.50] (26)
325000 Kamananui Pupukea	18.9 [14.1] (8)	26.3 [20.7] (4)	17.8 [13.3] (9)	16.2 [11.9] (11)	13.4 [9.72] (16)	11.5 [8.22] (22)	10.2 [7.25] (28)
330000 Kamananui Maunawai	20.3 [10.0] (8)	27.5 [12.7] (4)	19.2 [9.55] (9)	17.5 [8.78] (11)	14.7 [7.37] (16)	12.6 [6.33] (22)	11.2 [5.59] (28)
345000 Opaeula	18.0 [7.33] (8)	24.3 [8.26] (4)	17.1 [7.17] (9)	15.7 [6.87] (11)	13.3 [6.25] (16)	11.5 [5.63] (22)	10.3 [5.16] (28)

See footnote at end of table, p. 67.

Table 9.--Selected results of K-CERA analysis for the State of Hawaii--Continued

Station no. and name	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)						
	Current operation cost	Budget, in thousands of 1983 dollars					
	413.4	370	400	413.4	450	500	550
400000	20.5	28.5	22.8	21.5	18.7	16.3	14.6
Halawa	[7.67]	[10.9]	[8.61]	[8.10]	[6.97]	[6.02]	[5.33]
	(10)	(5)	(8)	(9)	(12)	(16)	(20)
404200	12.9	15.3	15.3	15.3	15.3	15.3	15.3
Pilipililau	[5.42]	[5.63]	[5.63]	[5.63]	[5.63]	[5.63]	[5.63]
	(6)	(4)	(4)	(4)	(4)	(4)	(4)
405100	7.77	9.95	9.95	8.65	7.13	6.24	5.66
Tunnel east	[4.42]	[6.62]	[6.62]	[5.25]	[3.87]	[3.22]	[2.90]
	(6)	(4)	(4)	(5)	(7)	(9)	(11)
405300	4.84	6.03	6.03	5.31	4.52	4.09	3.82
Tunnel west	[3.16]	[4.25]	[4.25]	[3.54]	[2.94]	[2.72]	[2.62]
	(6)	(4)	(4)	(5)	(7)	(9)	(11)
405500	21.4	26.0	26.0	23.4	19.9	17.6	16.0
Waikolu	[10.0]	[12.7]	[12.7]	[11.1]	[9.19]	[7.99]	[7.16]
	(6)	(4)	(4)	(5)	(7)	(9)	(11)
408000	14.7	17.8	17.8	16.1	13.7	12.1	11.0
Waikolu pipeline	[9.94]	[12.4]	[12.4]	[11.0]	9.13	[7.96]	[7.12]
	(6)	(4)	(4)	(5)	(7)	(9)	(11)
414000	47.9	50.0	47.9	47.2	46.0	44.8	44.1
Kaunakakai	[45.0]	[45.9]	[45.0]	[44.7]	[44.1]	[43.5]	[43.1]
	(6)	(4)	(6)	(7)	(10)	(15)	(20)
419500	34.5	37.6	26.9	23.6	19.1	16.5	14.3
Papio	[15.0]	[16.5]	[11.1]	[9.64]	[7.66]	[6.59]	[5.67]
	(6)	(5)	(10)	(13)	(20)	(27)	(36)
501000	38.3	45.7	35.8	33.8	29.4	25.8	23.4
Palikea	[13.1]	[13.8]	[12.8]	[12.7]	[12.2]	[11.7]	[11.2]
	(6)	(4)	(7)	(8)	(11)	(15)	(19)
508000	11.8	14.1	14.1	14.1	14.1	12.8	11.8
Hanawi	[5.64]	[6.41]	[6.41]	[6.41]	[6.41]	[6.01]	[5.64]
	(6)	(4)	(4)	(4)	(4)	(5)	(6)

See footnote at end of table, p. 67.

Table 9.--Selected results of K-CERA analysis for the State of Hawaii--Continued

Station no. and name	Current operation cost 413.4	Budget, in thousands of 1983 dollars 370	400	413.4	450	500	550
	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)						
512000 Koolau Nahiku	5.00 [1.47] (6)	6.00 [1.55] (4)	6.00 [1.55] (4)	6.00 [1.55] (4)	6.00 [1.55] (4)	6.00 [1.55] (4)	5.43 [1.50] (5)
518000 Wailuaiki	11.6 [3.60] (6)	14.1 [4.46] (4)	14.1 [4.46] (4)	14.1 [4.46] (4)	14.1 [4.46] (4)	14.1 [4.46] (4)	12.7 [3.96] (5)
523000 Koolau Keanae	4.53 [4.12] (6)	5.08 [4.60] (4)	5.08 [4.60] (4)	5.08 [4.60] (4)	5.08 [4.60] (4)	5.08 [4.60] (4)	4.78 [4.34] (5)
531000 Kula	28.8 [20.3] (5)	25.5 [19.7] (8)	24.9 [19.5] (9)	24.3 [19.4] (10)	22.8 [19.1] (14)	21.6 [18.7] (19)	20.8 [18.5] (24)
538000 Spreckels	11.7 [4.19] (6)	13.9 [4.38] (4)	13.9 [4.38] (4)	13.9 [4.38] (4)	11.7 [4.19] (6)	9.83 [4.04] (9)	9.05 [3.97] (11)
541000 Koolau Haipuena	2.77 [.691] (6)	3.35 [.82] (4)	3.35 [.82] (4)	3.35 [.82] (4)	2.77 [.69] (6)	2.28 [.58] (9)	2.07 [.54] (11)
541500 Manuel	22.2 [4.30] (6)	26.9 [5.00] (4)	22.2 [4.30] (6)	20.7 [4.03] (7)	17.4 [3.46] (10)	14.8 [2.97] (14)	13.4 [2.71] (17)
587000 Honopou	13.7 [3.32] (12)	13.7 [3.32] (12)	13.7 [3.32] (12)	13.7 [3.32] (12)	13.7 [3.32] (12)	12.3 [3.01] (15)	10.9 [2.70] (19)
588000 Wailoa	5.76 [2.02] (5)	6.38 [2.20] (4)	6.38 [2.20] (4)	6.38 [2.20] (4)	6.38 [2.20] (4)	5.76 [2.02] (5)	4.93 [1.77] (7)
589000 Hamakua Honopou	23.3 [6.71] (5)	25.7 [6.88] (4)	20.1 [6.50] (7)	18.0 [6.36] (9)	15.9 [6.22] (12)	13.7 [6.05] (17)	12.6 [5.93] (21)

See footnote at end of table, p. 67.

Table 9.--Selected results of K-CERA analysis for the State of Hawaii--Continued

Station no. and name	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)						
	Current operation cost	Budget, in thousands of 1983 dollars					
	413.4	370	400	413.4	450	500	550
592000 Lowrie	14.7 [4.10] (5)	16.2 [4.25] (4)	12.6 [3.89] (7)	11.9 [3.81] (8)	9.88 [3.56] (12)	8.43 [3.27] (17)	7.83 [3.13] (20)
594000 Haiku	30.8 [7.87] (5)	30.8 [7.87] (5)	22.6 [7.37] (10)	20.8 [7.25] (12)	17.9 [7.02] (17)	15.7 [6.77] (23)	14.2 [6.57] (29)
599500 Opana	14.1 [3.40] (5)	15.6 [3.67] (4)	14.1 [3.40] (5)	12.9 [3.17] (6)	10.1 [2.58] (10)	8.30 [2.16] (15)	7.21 [1.89] (20)
618000 Kahakuloa	15.2 [2.52] (7)	16.3 [2.72] (6)	16.3 [2.72] (6)	16.3 [2.72] (6)	15.2 [2.52] (7)	13.4 [2.23] (9)	12.2 [2.02] (11)
620000 Honokohau	13.0 [2.21] (5)	14.8 [2.44] (4)	14.5 [2.44] (4)	14.5 [2.44] (4)	14.5 [2.44] (4)	11.9 [2.03] (6)	11.1 [1.89] (7)
638500 Kahoma	78.5 [77.3] (10)	56.0 [54.5] (20)	38.8 [37.4] (40)	35.6 [34.2] (47)	29.7 [28.4] (66)	25.5 [24.4] (88)	23.1 [22.0] (107)
700000 Waiakea	8.57 [1.04] (12)	8.57 [1.04] (12)	8.57 [1.04] (12)	8.57 [1.04] (12)	8.57 [1.04] (12)	8.57 [1.04] (12)	8.24 [1.01] (13)
700900 Olaa	10.5 [2.90] (8)	14.6 [4.18] (4)	11.2 [3.12] (7)	11.2 [3.12] (7)	8.96 [2.46] (11)	7.70 [2.11] (15)	6.86 [1.88] (19)
700950 Lyman	10.5 [4.54] (8)	14.2 [5.42] (4)	11.1 [4.71] (7)	11.1 [4.71] (7)	9.08 [4.08] (11)	7.88 [3.64] (15)	7.05 [3.31] (19)
704000 Wailuku Piihonua	19.0 [5.17] (8)	23.7 [6.00] (5)	17.1 [4.76] (10)	16.3 [4.58] (11)	13.6 [3.93] (16)	11.7 [3.04] (22)	10.4 [3.04] (28)

See footnote at end of table, p. 67.

Table 9.--Selected results of K-CERA analysis for the State of Hawaii--Continued

Station no. and name	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)						
	Current operation cost	Budget, in thousands of 1983 dollars					
	413.4	370	400	413.4	450	500	550
713000 Wailuku Hilo	15.9 [4.43] (8)	15.9 [4.43] (8)	11.0 [3.11] (17)	10.4 [2.94] (19)	9.13 [2.58] (25)	7.62 [2.16] (36)	6.90 [1.96] (44)
717000 Honolii	17.3 [.73] (8)	19.8 [.81] (6)	18.4 [.77] (7)	17.3 [.73] (8)	14.2 [.62] (12)	12.3 [.55] (16)	11.3 [.51] (19)
720000 Kawainui	12.6 [3.60] (6)	15.3 [4.34] (4)	12.6 [3.60] (6)	11.0 [3.13] (8)	9.42 [2.68] (11)	8.10 [2.30] (15)	7.21 [2.06] (19)
720300 Kawaiki	11.6 [2.30] (6)	14.1 [2.82] (4)	11.6 [2.30] (6)	10.1 [1.99] (8)	8.65 [1.70] (11)	7.43 [1.46] (15)	6.61 [1.29] (19)
720500 Hamakua Kawaiki	15.8 [6.58] (6)	18.7 [6.86] (4)	15.8 [6.58] (6)	14.1 [6.42] (8)	12.4 [6.27] (11)	11.1 [6.13] (15)	10.2 [6.01] (19)
724800 Hamakua Alakahi	15.7 [7.02] (6)	18.6 [7.63] (4)	15.7 [7.02] (6)	13.9 [6.56] (8)	12.1 [6.00] (11)	10.5 [5.41] (15)	9.45 [4.94] (19)
725000 Alakahi	13.8 [6.88] (6)	16.1 [7.16] (4)	13.8 [6.88] (6)	12.4 [6.72] (8)	11.1 [6.55] (11)	9.97 [6.40] (15)	9.26 [6.27] (19)
726000 Hamakua Waimea	16.0 [5.13] (6)	17.4 [5.33] (5)	12.7 [4.50] (10)	12.1 [4.38] (11)	10.2 [3.86] (16)	8.76 [3.43] (22)	7.80 [3.10] (28)
727000 Hamakua Puukapu	31.0 [5.52] (6)	33.8 [5.67] (5)	24.4 [5.11] (10)	23.3 [5.02] (11)	19.5 [4.65] (16)	16.7 [4.28] (22)	14.9 [3.97] (28)
756000 Kohakohau	17.6 [2.81] (6)	19.2 [2.86] (5)	13.8 [2.69] (10)	13.2 [2.67] (11)	11.1 [2.60] (16)	9.53 [2.53] (22)	8.52 [2.47] (28)

See footnote at end of table, p. 67.

Table 9.--Selected results of K-CERA analysis for the State of Hawaii--Continued

Station no. and name	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)						
	Current operation cost	Budget, in thousands of 1983 dollars					
	413.4	370	400	413.4	450	500	550
758000 Waikoloa	11.1 [1.51] (6)	12.1 [1.54] (5)	8.68 [1.46] (10)	8.30 [1.45] (11)	6.94 [1.42] (16)	5.97 [1.39] (22)	5.33 [1.37] (28)
759000 Hauani	18.7 [4.97] (6)	20.4 [5.06] (5)	14.9 [4.78] (10)	14.3 [4.74] (11)	12.11 [4.62] (16)	10.6 [4.51] (22)	9.57 [4.41] (28)
764000 Hilea	41.9 [3.50] (6)	41.9 [3.50] (6)	31.2 [3.32] (11)	27.8 [3.25] (14)	23.4 [3.14] (20)	20.5 [3.04] (26)	18.3 [2.96] (33)

1/ Square root of averaged station variance.

Table 10.--Selected results of K-CERA analysis for the Other Pacific Areas

Station no. and name	Current operation cost	Budget, in thousands of 1983 dollars					
	157.2	145	150	157.2	175	200	250
	Standard error (SE) of instantaneous discharge, in percent [Equivalent Gaussian spread (EGS)] (Number of visits per year to site)						
Average SE per station for the Other Pacific Areas[1/]	25.9	32.0	26.7	23.2	18.8	15.6	12.2
EGS for the Other Pacific Areas	[13.3]	[17.0]	[14.5]	[12.5]	[10.2]	[8.5]	[6.6]
800000 Denni	29.9 [24.7] (12)	29.9 [24.7] (12)	29.9 [24.7] (12)	29.9 [24.7] (12)	24.0 [19.7] (21)	19.6 16.0 (33)	15.4 [12.4] (55)
801000 Talofofo	52.1 [33.0] (12)	52.1 [33.0] (12)	52.1 [33.0] (12)	52.1 [33.0] (12)	40.3 [24.9] (21)	32.5 [19.6] (33)	25.3 [15.0] (55)
809600 La Sa Fua	28.3 [16.8] (11)	36.2 [21.3] (6)	28.3 [16.8] (11)	22.8 [13.4] (18)	18.3 [10.6] (29)	15.0 [8.59] (44)	11.5 [6.57] (75)
840000 Tinaga	39.6 [19.2] (11)	47.7 [22.2] (7)	36.9 [18.2] (13)	29.9 [15.1] (21)	23.9 [12.2] (34)	19.5 [9.93] (52)	15.2 [7.68] (87)
847000 Imong	31.7 [21.3] (11)	44.6 [27.0] (4)	33.9 [22.2] (9)	28.5 [19.8] (15)	23.3 [17.0] (26)	18.8 [13.9] (44)	14.3 [10.7] (80)
848100 Almagosa	21.5 [12.4] (11)	31.6 [17.1] (4)	24.4 [13.7] (8)	20.1 [11.7] (13)	16.1 [9.53] (22)	13.2 [7.88] (34)	10.2 [6.08] (59)
848500 Maulap	17.3 [6.67] (11)	26.9 [11.9] (4)	20.0 [7.9] (8)	16.0 [6.08] (13)	12.5 [4.60] (22)	10.1 [3.72] (34)	7.72 [2.81] (59)

See footnote at end of table, p. 71.

Table 10.--Selected results of K-CERA analysis for the Other Pacific Areas--Continued

Station no. and name	Current operation cost	Budget, in thousands of 1983 dollars					
	157.2	145	150	157.2	175	200	250
	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)						
854500 Ugum	14.5 [3.88] (11)	22.7 [6.81] (4)	17.8 [4.9] (7)	14.5 [3.88] (11)	11.5 [3.00] (18)	9.13 [2.36] (29)	7.53 [1.94] (43)
858000 Ylig	32.4 [3.88] (11)	41.2 [18.2] (6)	32.4 [16.0] (11)	26.7 [14.4] (18)	22.1 [12.8] (29)	18.5 [11.2] (44)	14.5 [9.01] (76)
890600 Diongradid	16.1 [16.0] (11)	22.1 [3.63] (6)	22.1 [3.63] (6)	22.1 [3.63] (6)	18.4 [2.78] (9)	14.9 [2.16] (14)	11.5 [1.62] (24)
890900 Tabecheding	11.1 [2.32] (12)	15.2 [4.49] (6)	15.2 [4.49] (6)	15.2 [4.50] (6)	15.2 [4.50] (6)	12.7 [3.69] (9)	9.71 [2.75] (16)
891310 Kmekumel	15.3 [3.19] (12)	20.7 [6.92] (6)	20.7 [6.92] (6)	20.7 [6.92] (6)	17.4 [5.98] (9)	14.3 [5.03] (14)	11.3 [4.06] (23)
891400 Ngerdorch	13.4 [5.35] (12)	18.2 [7.01] (6)	18.2 [7.01] (6)	18.2 [7.01] (6)	17.1 [6.45] (7)	13.9 [5.08] (11)	10.8 [3.81] (19)
892000 Qatliw	26.4 [4.85] (18)	38.0 [14.9] (8)	27.1 [10.9] (17)	21.8 [8.85] (27)	17.1 [6.91] (45)	14.2 [5.74] (66)	11.2 [4.57] (106)
892400 Qaringeel	31.7 [20.5] (18)	42.8 [25.0] (8)	32.4 [20.8] (17)	27.0 [18.0] (27)	21.7 [14.7] (45)	18.2 [12.4] (66)	14.5 [9.86] (106)
893100 Burong	27.9 [13.4] (18)	34.4 [15.6] (11)	25.0 [12.3] (23)	19.6 [9.9] (39)	15.6 [7.84] (63)	13.9 [6.95] (80)	11.0 [5.50] (127)
893200 Mukong	30.8 [27.6] (18)	36.7 [33.2] (11)	27.8 [24.8] (23)	21.8 [19.2] (39)	17.3 [15.0] (63)	15.4 [13.3] (80)	12.2 [10.5] (127)

See footnote at end of table, p. 71.

Table 10.--Selected results of K-CERA analysis for the Other Pacific Areas--Continued

Station no. and name	Current operation cost	Budget, in thousands of 1983 dollars					
	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)						
	157.2	145	150	157.2	175	200	250
893400 Eyeb	39.2 [32.8] (18)	46.4 [38.5] (11)	35.7 [29.8] (23)	28.4 [23.6] (39)	22.6 [18.6] (63)	20.1 [16.5 (80)	15.5 [12.6] (135)
893800 Wichen	43.8 [16.2] (10)	45.9 [17.0] (9)	34.4 [12.8] (17)	28.1 [10.4] (26)	23.4 [8.64] (38)	18.6 [6.82] (61)	14.8 [5.42] (97)
897600 Nanpil	18.8 [11.9] (12)	25.2 [16.7] (6)	20.4 13.0 (10)	16.5 [10.2] (6)	12.9 [7.81] (27)	10.7 [6.37] (40)	8.70 [5.17] (61)
897900 Lewi	21.2 [15.5] (12)	27.0 [19.2] (6)	22.6 [16.4] (10)	19.0 [13.9] (16)	15.2 [11.1] (27)	12.7 [9.25] (40)	10.4 [7.53] (61)
898600 Luhpwor	18.1 [7.27] (12)	24.1 [8.18] (6)	22.6 [7.91] (7)	19.5 [7.45] (16)	16.1 7.04 (16)	13.5 [6.77] (25)	11.1 [6.48] (42)
899750 Malem	12.5 [8.78] (18)	20.4 [16.0] (6)	19.1 [14.7] (7)	15.7 [11.5] (11)	12.5 [8.78] (18)	10.3 [7.10] (27)	8.14 [5.53] (44)
899800 Tofol	9.94 [7.00] (18)	14.7 [9.56] (6)	14.7 [9.56] (6)	12.0 [8.2] (11)	9.94 [7.00] (18)	8.44 [6.03] (27)	6.84 [4.93] (44)
912000 Pago	17.4 [9.64] (12)	22.9 [11.1] (6)	19.5 [10.3] (9)	16.4 [9.28] (14)	13.5 [8.09] (22)	11.2 [6.86] (34)	8.41 [5.25] (62)
920500 Aasu	14.5 [8.97] (8)	16.3 [9.81] (6)	16.3 [9.81] (6)	16.3 [9.81] (27)	12.7 [8.00] (11)	10.5 [6.68] (17)	8.30 [5.29] (28)
931000 Atauloma	22.9 [17.9] (12)	31.0 [24.8] (6)	27.5 [21.8] (8)	21.3 [16.6] (14)	17.1 [13.1] (22)	14.2 [10.7] (32)	11.0 [8.24] (53)

See footnote at end of table, p. 71.

Table 10.--Selected results of K-CERA analysis for the Other Pacific Areas--Continued

Station no. and name	Standard error of instantaneous discharge, in percent [Equivalent Gaussian spread] (Number of visits per year to site)						
	Current operation cost	Budget, in thousands of 1983 dollars					
	157.2	145	150	157.2	175	200	250
931500 Asili	13.4 [12.7] (12)	14.7 [13.4] (6)	14.7 [13.4] (6)	14.7 [13.4] (6)	13.7 [12.9] (10)	12.7 [12.2] (18)	10.8 [10.5] (42)
933500 Leafu Leone	10.4 [8.83] (12)	12.8 [10.5] (6)	12.8 [10.5] (6)	12.8 [10.5] (6)	11.1 [9.30] (10)	9.03 [7.72] (18)	6.26 [5.36] (42)
948000 Afuelo	28.3 [23.7] (12)	33.3 [25.7] (6)	32.1 [25.2] (7)	28.3 [23.7] (12)	24.2 [21.3] (23)	19.8 [17.9] (45)	15.1 [13.8] (89)
963900 Leafu	25.6 [17.5] (12)	35.5 [25.3] (6)	29.4 [20.5] (9)	23.8 [16.1] (14)	19.0 [12.6] (22)	15.8 [10.3] (32)	12.4 [8.02] (52)

1/ Square root of averaged station variance.

A minimum budget of $370,000 is required to operate the 92-station program for the State of Hawaii; a budget less than this does not permit proper service and maintenance of the gages and recorders. Stations would have to be eliminated from the program if the budget fell below this minimum. At the minimum budget, the average standard error is 23.7 percent. The minimum standard error of 3.4 percent would occur at station 541000 (Koolau Haipuena), while the maximum of 56.0 percent would occur at station 638500 (Kahoma).

As explained earlier, stations 303000 (Punaluu) and 899620 (Melo) were not included in the calculations for standard errors.

The maximum budget analyzed for the State of Hawaii program was $550,000, which resulted in an average standard error of estimate of 12.9 percent. For the $550,000 budget, the extremes of standard error are 2.1 percent at station 541000 (Koolau Haipuena), and 44.1 percent at station 414000 (Kaunakakai). Thus, it is apparent that improvements in accuracy of streamflow records can be obtained if larger budgets become available.

It would be possible to reduce the average standard error for the Other Pacific Areas by a policy change while maintaining the same budget of $157,250. In this case, the average standard error would decrease from 25.9 percent to 23.2 percent. Extremes of standard error in individual sites would be 12 and 52 percent for stations 899800 (Tofol) and 801000 (Talofofo), respectively.

A minimum budget of $145,000 is required to operate the 32-station program for the Other Pacific Areas; a budget less than this does not permit proper service and maintenance of the gages and recorders. Stations would have to be eliminated from the program if the budget fell below this minimum. At the minimum budget, the average standard error is 32.0 percent. The minimum standard error of 12.8 percent would occur at station 933500 (Leafu Leone), while the maximum of 52.1 percent would occur at station 801000 (Talofofo).

The maximum budget analyzed for the Other Pacific Areas program was $250,000, which resulted in an average standard error of estimate of 12.2 percent. For the $250,000 budget, the extremes of standard error are 6.3 percent at station 933500 (Leafu Leone), and 25.3 percent at station 801000 (Talofofo). Thus, it is apparent that significant improvements in accuracy of streamflow records can be obtained if larger budgets become available.

Conclusions from the K-CERA Analysis

As a result of the K-CERA analysis, the following suggestions are offered:

1. The policy for the definition of field activities in the stream-gaging program should be altered to improve the current average standard errors of estimate of streamflow records to 17.7 percent with the current budget of $413,400 for the State of Hawaii and 23.2 percent with the current budget of $157,200 for the Other Pacific Areas. This shift would result in some increases and some decreases in accuracy of records at individual sites.
2. After implementing the first suggestion, the amount of funding for stations with accuracies that are not acceptable for the data uses should be renegotiated with the data users.
3. The funding made available by implementation of the second suggestion should be used to improve the accuracy of records at appropriate stations to an acceptable level.
4. Schemes for reducing the probabilities of missing record, for example increased use of local gage observers and satellite relay of data, should be explored and evaluated as to their cost-effectiveness in providing streamflow information.

SUMMARY

Currently, there are 124 continuous stream gages being operated in the Hawaii District at a cost of $570,620. Thirteen separate sources of funding contribute to this program. There are parts of some islands in which streamflow data sites seem too sparse to provide valid estimates of streamflow characteristics. This paucity was caused by discontinuance of gages in the past for economic, technical and political reasons. No additional gages are suggested. The current 124 stations should be maintained in the program for the foreseeable future.

The current policy for operation of the 124-station program requires a budget of $570,620 per year. It was shown that the overall level of accuracy of the records could be improved with the same budget if the allocation of gaging resources among gages was altered. It is suggested that this alteration takes place. After this alteration funds should be renegotiated to improve the accuracy of record at sites where accuracy of data are not acceptable.

A major component of the error in streamflow records is caused by loss of primary record (stage or other correlative data) at the stream gages because of malfunctions of sensing and recording equipment. Upgrading of equipment and development of strategies to minimize lost record appear to be key actions required to improve the reliability and accuracy of the streamflow data generated in the Hawaii District.

Studies of the cost-effectiveness of the stream-gaging program should be continued and should include investigation of the optimum ratio of discharge measurements to total site visits for each station, as well as investigation of cost-effective ways of reducing the probabilities of lost correlative data. Future studies also will be required because of changes in demands for streamflow information with subsequent addition and deletion of stream gages. Such changes will affect the operation of other stations in the program both because of the dependence between stations of the information that is generated (data redundancy) and because of the dependence of the costs of collecting the data from which the information is derived.

REFERENCES CITED

Benson, M. A., and Carter, R. W., 1973, A national study of the streamflow data-collection program: U.S. Geological Survey Water-Supply Paper 2028, 44 p.

Carter, R. W., and Benson, M. A., 1970, Concepts for design of streamflow data programs: U.S. Geological Survey Open-File Report, 33 p.

Draper, N. R., and Smith, H., 1966, Applied regression analysis: New York, N. Y., John Wiley and Sons, 2d ed., 709 p.

Fontaine, R. A., Moss, M. E., Smath, J. A., and Thomas, W. O., Jr., 1984, Cost-effectiveness of the stream-gaging program in Maine--a prototype for nation-wide implementation: U.S. Geological Survey Water-Supply Paper 2244, 39 p.

Gelb, A., ed., 1974, Applied optimal estimation: The Massachusetts Institute of Technology Press, Cambridge, Mass., 374 p.

Gilroy, E. J., and Moss, M. E., 1981, Cost-effective stream-gaging strategies for the Lower Colorado River Basin: U.S. Geological Survey Open-File Report 81-1019, 42 p.

Hutchinson, N. E., 1975, WATSTORE User's guide, volume 1: U.S. Geological Survey Open-File Report 75-426, 791 p.

Keefer, T. N., 1974, Desktop computer flow routing: American Society of Civil Engineers Proceedings, Journal of the Hydraulics Division, v. 100, no. HY7, p. 1047-1058.

Keefer, T. N., and McQuivey, R. S., 1974, Multiple linearization flow routing model: American Society of Civil Engineers Proceedings, Journal of the Hydraulics Division, v. 100, no. HY7, p. 1031-1046.

Kleinbaum, D. G., and Kupper, L. L., 1978, Applied regression analysis and other multivariable methods: North Scituate, Mass., Duxbury Press, 556 p.

Mitchell, W. D., 1962, Effect of reservoir storage on peak flow: U.S. Geological Survey Water-Supply Paper 1580, p. C1-C25.

Moss, M. E., and Gilroy, E. J., 1980, Cost-effective stream-gaging strategies for the Lower Colorado River Basin: U.S. Geological Survey Open-File Report 80-1048, 111 p.

Moss, M. E., Gilroy, E. J., Tasker, G. D., and Karlinger, M. R., 1982, Design of surface-water data networks for regional information: U.S. Geological Survey Water-Supply Paper 2178, 33 p.

Riggs, H. C., 1973, Regional analysis of streamflow characteristics: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chapter B3, 15 p.

Thomas, D. M., and Benson, M. A., 1970, Generalization of streamflow characteristics from drainage-basin characteristics: U.S. Geological Survey Water-Supply Paper 1975, 55 p.

U.S. Geological Survey, 1981, Water resources data, Hawaii, water year 1981: U.S. Geological Survey Water-Data Report HI-81-1, v. 1. Hawaii, 266 p.

----- 1981, Water resources data for Hawaii and other Pacific areas, water year 1981: U.S. Geological Survey Water-Data Report HI-81-2, v. 2. Trust Territory of the Pacific Islands, Guam, American Samoa, and Northern Mariana Islands, 148 p.