A PRELIMINARY REPORT
ON
FLOOD HYDROLOGY AND URBAN WATER RESOURCES:
OAHU, HAWAII

by

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Project Completion Report
for
FLOOD HYDROLOGY AND URBAN WATER RESOURCES
OF THE ISLAND OF OAHU, HAWAII
PHASE I

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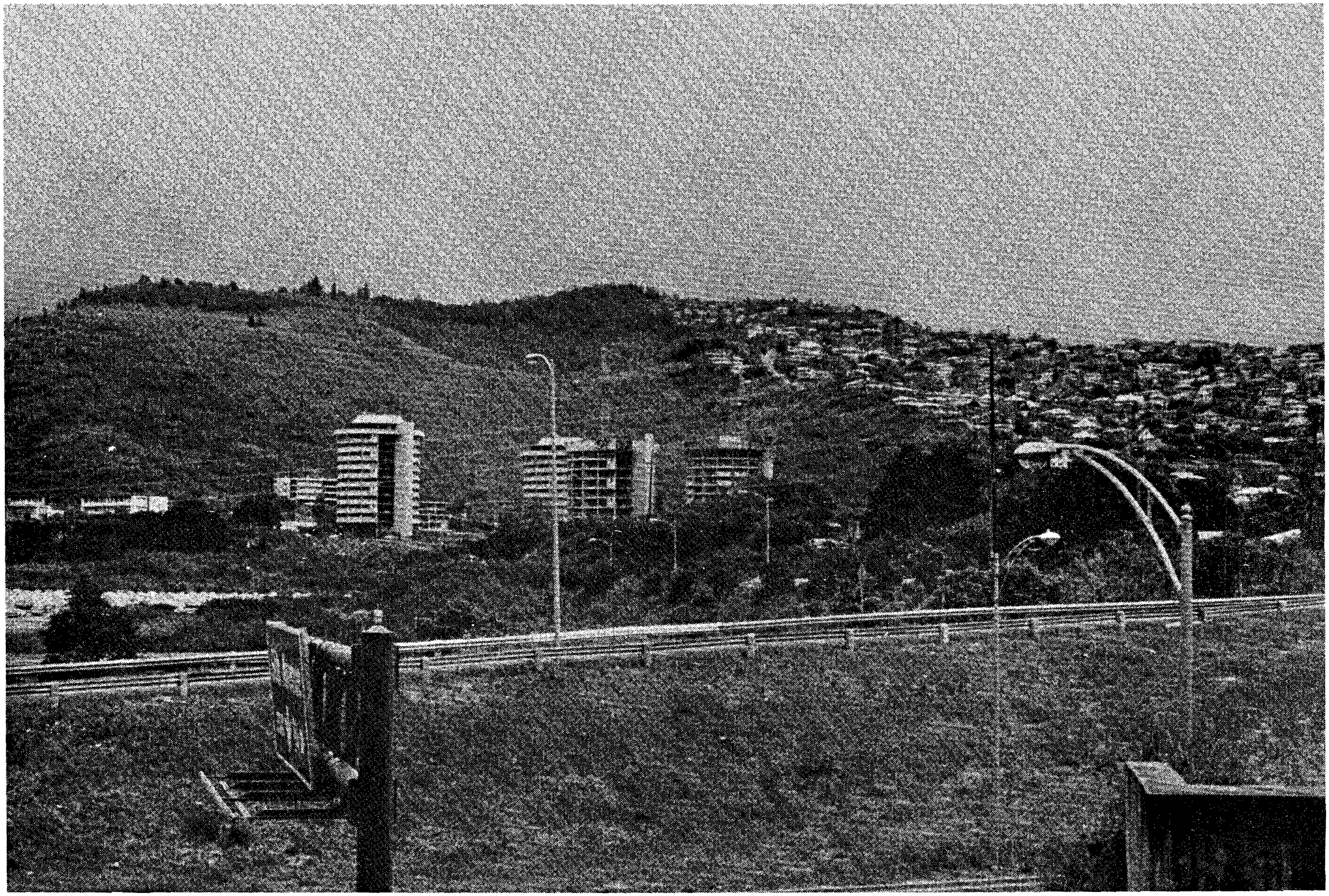

FRONTISPIECE: A view of undeveloped Waahila Ridge to the left and highly urbanized St. Louis Heights to the right taken from H-1 Freeway facing northeast.

ABSTRACT

Studies conducted during Phase I of the "Flood Hydrology and Urban Water Resources of the Island of Oahu, Hawaii" project, were divided into four major tasks.

The first is an examination of the causes of flooding and flood damages on Oahu. This task has been completed and data obtained reveals that historical floods in Oahu happened most frequently within the city limits of Honolulu and the Waialua area. Watersheds in Honolulu such as Kalihi, Manoa, Makiki, Moanalua, Nuuanu, Palolo and Pauoani were found to have frequent floods up to the 1940's; however, they have not been subjected to severe frequent floods for the past two decades. Watersheds such as Kailua, Kaneohe, and Waimanalo in windward Oahu and Aina Haina, Niu Valley, and Pearl City on the fringes of the city limits of Honolulu were reported to have more frequent floods in the past two decades. Some of the reason for the patterns of flooding are:

1. *The Honolulu district has the highest concentration of people and housing on the island.*
2. *The Waialua area is located downstream of many large streams of the island.*
3. *Kalihi, Manoa, Makiki, Moanalua watersheds have been urbanized in the early part of the century; therefore, the flood prevention system in these watersheds have been improved over these years.*

The second task was to evaluate the effect of urbanization upon flood hydrographs from selected watersheds in Oahu. In general, the effect of progress of urbanization on a watershed is evident in the increase in the flood peak and reduction in the time to peak. However, it is felt that this finding cannot be generalized. More hydrological data is needed to substantiate such a generalization.

The third task was to establish the rainfall-runoff data collection devices in the adjoined urban (St. Louis Heights) and natural (Waahila) watersheds. The installation and operation of two auto-recording raingages and two auto-recording water stage recorders were completed. These rainfall and runoff recording instruments will provide the required data for the hydrologic simulation modeling studies and for the evaluation of the effect of urbanization upon watershed hydrology.

The fourth task was to initiate the studies of watershed simulation models. Thus far, efforts have been concentrated on two watershed simulation models. One model utilizes an auto-optimal technique in determining the instantaneous unit hydrograph. The other model is a modification of the Kentucky Watershed Model to better fit Hawaiian conditions. Additional modifications are required before a good fit is achieved by both models.

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INTRODUCTION

Developmental patterns show that the urbanization of Oahu, where about 70 percent of the state's population is concentrated, generally started along the rather narrow coastal lands and then moved inland into the valleys and hillsides. The progressive inland expansion of urbanization forced the newer storm drainage systems to be connected to the existing older ones in the coastal area. Thus, an overload will result when the increments of urbanization ultimately exceed the capacity of the storm drainage systems. On the other hand, the change in land use of the watershed from natural to urban will undoubtedly affect the hydrological characteristics of the watershed. It is important that the effects of urbanization upon the flood hydrograph of a watershed are assessed so that such effects can be taken into consideration in the design of a storm drainage system for urban areas.

As urbanization continues to exert pressures and demands on the use of land, water, and other natural resources on Oahu, it has become increasingly evident that more knowledge is needed to be better able to utilize the available resources and to implement effective flood control measures.

As discussed in the report "Basic Information Needs in Urban Hydrology" by American Society of Civil Engineers (1969), the national investment in construction of storm drainage systems may reach $3.5 billion per year for the next ten years. However, urban water resources research and data gathering networks are not adequate to meet this decisionmaking requirement.

The objectives for the first phase of the project reported here are to gain a better understanding of the flood hydrology on Oahu from available data, to investigate the effect of urbanization upon the flood hydrographs from selected watersheds, to establish experimental watersheds to gather hydrological data, and to initiate studies of watershed simulation models which are suitable for Hawaiian watersheds.

AN EXAMINATION OF FLOOD OCCURRENCE AND DAMAGES ON OAHU

A. The Nature and Causes of Floods

Some understanding of floods can be obtained by learning the nature and causes of floods. Flood damages are significant because they affect human life and property. Large floods occurring in the wilderness have no significance because they do not damage human life and property, whereas, even a small overbank flow in an urban area is of serious consequence.

Floods caused by storms on Oahu may be attributed to any combination of the following causes:

1. Act of Nature
    a. Rainfall
        Intensity and distribution
        Duration
        Frequency (recurrence interval)
        Antecedent rains
        Season
    b. Type of storm
        Cyclonic disturbance
        Kona (thunderstorm)
    c. Overland flow and overflow of stream banks
    d. Sediment, falling trees, and other debris
2. Man's activities
    a. Obstruction of stream channel
    b. Use of flood plain
    c. Design of the storm drainage system
    d. Maintenance and operation of the drainage system
    e. Improvement of the existing drainage system

B. Measurable Characteristics of the Flood

Currently peak discharge, rainfalls, and some flood hydrographs which could also be measured, are being recorded in Oahu. Other characteristics of a flood, such as the locations of overbank flow; the duration, height, and area of inundation; deposition of sediment; and erosion are not being recorded as thoroughly as they should be. It is these unrecorded characteristics of floods that are essential for watershed planning and management, especially in areas which are being developed for urbanization.

C. Identifiable Damages from Flood

The existing system of flood damage documentation needs refinement. Without adequate flood damage measurements, the benefits of flood control may be difficult to evaluate and flood insurance policies difficult to administer. A post-flood survey of flood damages should itemize the following categories:

1. Human life

2. Public health
3. Properties
    - Business
    - Industry
    - Agriculture
    - Residence
    - Public
4. Services
    - Transportation
    - Communication
    - Utilities
5. Recreation and Wildlife

The Division of Water and Land Development (DOWALD), Department of Land and Natural Resources, State of Hawaii has prepared a set of flood damage survey forms in their Bulletin No. 15 (1963) which are adequate for flood damage survey. These forms have been reproduced and included as Appendix A in the present report.

D. Post-flood Summary (1860-1965)

An unpublished summary of post-flood reports for Oahu floods occurring between 1860 to 1965 has been compiled by the Division of Water and Land Development (DOWALD), Department of Land and Natural Resources, State of Hawaii. The following items were included in the survey:

- Date
- Watershed
- District or town
- River or stream
- Type of storm
- Estimated peak flow or 24-hour rainfall
- Flood damages
    - Life lost
    - Injury
    - Home damaged
    - Evacuation from home
    - Extent of damages
- Estimated flood damage
- Source of information

Others

Utilizing information obtained from the newspapers, the National Weather Service, and the Red Cross, the report provides a general description of floods on Oahu. However, the reported peak flow, amount of rainfall, extent of costs of flood damages are not detailed enough.

A qualitative understanding of flood hydrology on Oahu may be gained from the post-flood summary which is arranged according to districts in Table 1. As shown in Table 1, watersheds such as Kalihi, Manoa, Makiki, Moanalua, Nuuanu, Palolo, and Pauoani Streams, which had frequent floods in the past, have not been experiencing severe frequent floods for the past two decades while the frequency of floods in Kailua, Kaneohe, and Waimanalo in the Windward Oahu and Aina Haina, Niu Valley, and Pearl City have increased during the same period. The tabulated data also indicates that the Honolulu and Waialua areas have had frequent floods in the recent past. Some reason for these observations are:

1. The Kalihi, Manoa, Makiki, Moanalua, Palolo, and Pauoa watersheds have been urbanized in the earlier part of the century. In the process of urbanization, the flood control or flood prevention system have been subjected to nature's test. Thus, floods were reported more frequently during the developmental stage. With experience gained through the years, improvements have been made in the flood control or flood prevention systems. As a result, the flood damages have been reduced in the last two decades.
2. Kailua, Kaneohe, Aina Haina, Niu Valley, and Pearl City have been experiencing a rapid urbanization in the last two decades. The flood control or flood prevention systems in these areas may now be experiencing the same kinds of tests that Kalihi, Manoa, Makiki, and Palolo were subjected to earlier, therefore, more frequent floods were reported in the past two decades.

   Waimanalo is an old plantation town in Oahu. The frequent floods reported since 1951 may be caused by the existing storm drainage system not being maintained to the desired level. The growth of the town since 1950 has over-loaded its storm drainage system. Flood were frequently reported at a section of the highway near Waimanalo which may be one contributor to the frequent floods reported in Waimanalo.
3. The Honolulu area reported more floods than any other areas. This

TABLE 1. POST FLOOD REPORT SUMMARY.

PERIOD	NUMBER OF STORM FLOODS	ESTIMATED DAMAGES ($)
	HONOLULU CITY	
1874 - 1900	6	7,900
1901 - 1910	9	31,000
1911 - 1920	5	80,500
1921 - 1930	3	N/A [2]
1931- 1940	6	191,400
1941 - 1950	3	2,500
1951 - 1960	14	536,000
1961 - 1965	1	N/A
	KAILUA	
1927	1	50,000
1951 - 1960	5	160,000
1961 - 1965	8	35,000
	KAIMUKI	
1920	1	N/A
1921 - 1930	2	2,200
1931 - 1440	2	1,500
1943	1	16,000
	KALIHI	
1899 - 1892	2	N/A
1911 - 1920	2	N/A
1921 - 1930	5	N/A
1951 - 1959	3	N/A
1960	1	7,000
	KANEOHE	
1883	1	10,000
1917	2	N/A
1923	1	N/A
1932	1	17,500
1937	1	N/A
1951 - 1960	6	336,000
1961 - 1965	2	7,000,000
	MAKIKI	
1900	1	5,000
1906	1	N/A
1911 - 1920	6	85,500
1921 - 1930	6	10,000
1931 - 1940	2	4,500
1943	1	7,000
1965	1	5,000
	MANOA	
1886	1	N/A
1906	1	5,000
1911 - 1920	4	N/A
1921 - 1930	6	163,000
	MANOA (CONT'D)	
1941 - 1950	2	60,000
1951 - 1960	3	61,000
1961 - 1965	2	2,000
	MOANALUA	
1898	1	N/A
1915	1	N/A
1917	1	16,000
1921 - 1930	8	188,000
1939	2	5,500
1952	1	2,000
	NUUANU	
1862	1	N/A
1863	1	1,000
1867	1	N/A
1876	1	N/A
1880	1	500
1881 - 1890	5	14,300
1891 - 1900	4	N/A
1901 - 1910	4	15,000
1911 - 1920	4	191,000
1921 - 1930	11	243,500
1931 - 1940	5	795,500
1960	1	4,000
	PALOLO	
1911	1	N/A
1921 - 1930	8	103,200
1932 - 1933	2	6,500
1948	1	12,000
1951	1	1,000,000
1960	1	1,000
1963	1	750,000
	PAUOA	
1879	1	12,000
1886	1	4,000
1900	1	N/A
1915 - 1917	2	75,500
1927	2	57,000
	PEARL CITY	
1904	1	1,600
1907	1	5,000
1935	1	200,000
1954	1	30,000
1955	1	250,000
1956	1	N/A
	PUUNUI	
1899	1	N/A
1930	1	10,000
1932	1	100,000
1960	1	7,000
	WAHIAWA	
1910	1	10,000
1932	1	5,500
1936	1	N/A
1951	1	1,200
1960	1	30,000
1961	1	N/A
1965	1	350,000
	WAIALUA (KAHANA WATERSHED)	
1874	1	3,000
1879	1	1,000
1898	1	N/A
1910	1	10,000
1918	1	8,500
1920	1	1,700
1921 - 1930	3	42,000
1931 - 1940	8	182,400
1951 - 1960	2	103,000
1961 - 1965	3	245,000
	WAIANAE	
1900	1	5,000
1915	1	N/A
1918	1	5,000
1931 - 1940	3	5,000
1950 - 1957	3	3,6000
	WAIKIKI	
1884	1	N/A
1898	1	N/A
1918	1	2,000
1921 - 1930	8	N/A
1931 - 1940	7	N/A
1943	1	7,000
	WAIMANALO	
1886	1	2,000
1902	1	2,500
1932	1	N/A
1943	1	2,000
1951 - 1960	8	549,000

[1] THIS TABLE SUMMARIZES UNPUBLISHED DATA FOR 1860 - 1965 COMPILED BY "DOWALD."

[2] N/A = DATA NOT AVAILABLE

phenomenon can be explained by the fact that this area has the highest concentration of people and housing on the island. The chances of flooding from storm runoff are much higher in Honolulu than other place on the island.

4. Waialua, a district located in the northern part of the island, is an agricultural area. An irrigation canal system above the town collects water from many streams. The presence of many large streams and the bridges, irrigation canals, and roadways which cross these streams are responsible for the frequent reports of floods in this area.

In the flood control study by DOWALD (1963) the number of lives lost from floods (1867-1961) and annual flood damage (1900-1961) are summarized for the Hawaiian islands. The summaries of number of lives lost from storm floods (1867-1970) and annual storm flood damage (1900-1970) for the island of Oahu are summarized in Table 2 and Table 3, respectively, in this report, using data reported by Vaudrey (1963) and DOWALD (1965, 1971, 1968, 1968, and 1969). Tables 2 and 3 shows that the storm flood damages were greater during the period between 1951-1971 than the period before 1951; while the loss of lives was lower during the period between 1961-1971 than the period before 1951.

E. Means for Reduction of Flood Damage

Because of the limited land resources on Oahu, many effective flood prevention methods are not practical. For instance, according to Chow (1966), the construction of auxillary or bypass flood channels, flood control reservoirs, and flood walls and levees are not feasible for the highly populated city of Honolulu. However, there are other alternatives for reducing flood damages on Oahu despite high rainfall intensity and flooding caused by rising streams. The following are optional components for flood prevention plans for Oahu:

1. Stream channel and drainage system improvement
2. Flood forecasting and establishment of a flood warning system
3. Emergency evacuation
4. Land use zoning
5. Flood plain regulation
6. Building code and urban renewal
7. Flood insurance
8. Water resources systems planning

TABLE 2. SUMMARY OF HUMAN LIVES LOST FROM STORM FLOODS ON OAHU (1867-1970).

YEAR	TYPE OF STORM	NUMBER OF LIVES LOST
1867	RAINSTORM	1
1876	RAINSTORM	1
1879	RAINSTORM	3
1898	RAINSTORM	5[1]
1900	RAINSTORM	1
1911	RAINSTORM	1
1916	RAINSTORM	1
1921	RAINSTORM	4
1927	RAINSTORM	1
1930	RAINSTORM	15
1932	RAINSTORM	1
1935	RAINSTORM	14
1948	RAINSTORM	1
1949	RAINSTORM	2
1950	RAINSTORM	1
1951	RAINSTORM	2[1]
1954	RAINSTORM	2
1955	RAINSTORM	2[1]
1958	RAINSTORM	1
1959	HURRICANE	1
1963	RAINSTORM	3

[1]NUMBER OF HUMAN LIVES LOST DIFFER FROM TABLE 1.

TABLE 3. SUMMARY OF ANNUAL STORM FLOOD DAMAGE ON OAHU (1900-1970).

YEAR	ESTIMATED AMOUNT OF DAMAGE	YEAR	ESTIMATED AMOUNT OF DAMAGE
1900	33,000	1939	24,000
1901	8,000	1940	4,000
1902	18,000	1943	10,000
1904	25,000	1946	12,000
1906	25,800	1947	25,000
1907	33,000	1948	41,000
1909	8,000	1949	362,000
1910	8,000	1950	10,000
1914	70,000	1951	2,473,500
1915	30,000	1952	11,000
1916	100,000	1953	18,000
1917	215,000	1954	1,394,000
1918	35,000	1955	1,185,000
1919	8,000	1956	530,000
1920	7,500	1957	27,000
1921	225,000	1958	525,000
1922	18,000	1959	1,000,000
1923	105,000	1960	76,000
1924	5,000	1961	7,000
1927	98,000	1963	2,041,200
1930	210,000	1964	140,000
1932	175,000	1965	593,000
1933	7,000	1967	1,029,400
1935	17,000	1968	1,243,000
1936	26,000	1969	705,100
1937	5,000	1971	97,050
1938	4,000		

[1]1900 TO 1961 DATA WERE ESTIMATED FROM DOWALD BULLETIN 15, 1963, "FLOOD CONTROL AND FLOOD WATER CONSERVATION IN HAWAII" VOL. 1. FIGURE 15.

9. Regional development planning

EFFECTS OF URBANIZATION UPON FLOOD HYDROGRAPHS FROM SELECTED WATERSHEDS IN OAHU

The two most important characteristics of flood hydrographs are the peak discharge and duration of the hydrograph. To evaluate the effects of urbanization upon the flood hydrographs of selected watersheds, at least one stream gaging station should have been in operation for a long period and the watershed should have experienced substantial urbanization. It has found that there are only a few watersheds on Oahu that meet these requirements. These watersheds are Palolo, Kalihi, Wailupe, and Kamooalii. The progress of urbanization of these selected watersheds from 1945 to 1970 is plotted in Figure 1.

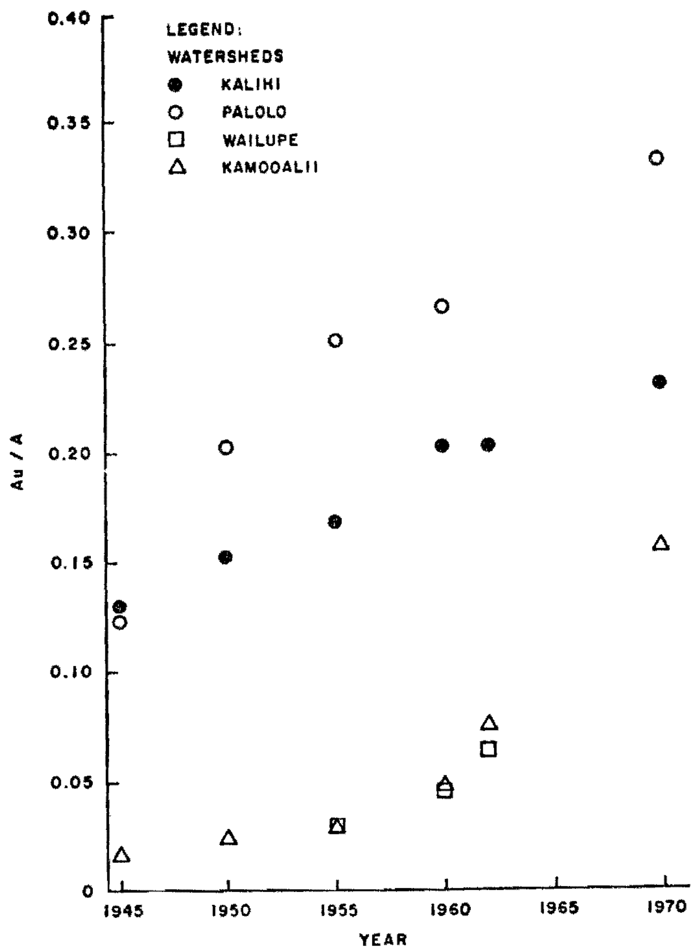

FIGURE 1. PROGRESS OF URBANIZATION OF SELECTED WATERSHEDS ON OAHU (1945-1970).

Following Wu's method (Wu, 1969) for determining the peak discharge Q_p, the time to peak t_p, the recession constant K_1, the effective rainfall R, the results of an extensive evaluation for the Palolo watershed are shown in Table 4. This was possible because the urban area in the Palolo

TABLE 4. IMPORTANT FLOOD HYDROGRAPH CHARACTERISTICS OF THE PALOLO WATERSHED, OAHU.

STREAM GAGING STATION NO.	DRAINAGE AREA/ACRE	DATE	TIME TO PEAK (HOURS)	DURATION INDEX (HOURS)	PEAK DISCHARGE (CFS)	RAINFALL INDEX (INCHES)
2440	755	5-16-27	1.00	1.96	1160	2.03
		11-17-48	1.00	1.72	950	1.43
		12-30-60	0.50	0.91	1100	1.12
		11-14-65	1.65	2.28	428	0.97
		1-27-68	0.80	1.57	214	0.46
		4-16-68	0.75	1.52	114	0.16
2460	666	10-15-38	0.91	1.77	931	1.35
		11-17-49	0.75	1.77	781	1.06
		3-06-63	0.67	1.20	406	0.37
		1-27-68	0.75	1.01	115	0.39
		3-16-68	0.40	0.86	507	1.18
		11-14-69	1.35	1.97	92	0.23
		1-30-69	1.40	1.74	139	0.37
		1-03-70	2.50	2.75	243	0.95
2470	2323	12-03-50	0.92	2.12	2090	1.23
		3-11-51	0.50	1.89	1180	0.77
		12-29-60	0.33	0.67	1460	0.45
		2-04-65	0.25	0.66	1927	0.66
		10-13-65	0.27	0.69	1061	0.52
		11-12-65	0.62	1.19	1095	0.53
		11-14-65	1.00	1.83	3520	1.33
		1-27-68	0.41	1.66	1150	0.35
		3-16-69	0.73	1.48	674	0.28
		11-14-69	0.50	1.09	784	0.41

watershed increased from 12.4 percent in 1945 to 33 percent in 1970. As shown in the Table 4, the records of stream gaging station No. 2470 after 1960 indicate that there is generally an increase in peak discharges.

However, there is very little urban development in the areas above stream gaging stations No. 2440 and 2460. Therefore, the data from these two gages (shown in Table 4) can be considered as the peak discharges for an undeveloped or natural watershed. Because the characteristics of the rainfall have not been studied in detail and based on data in Table 4, the plot of the peak discharges versus rainfall for Palolo watershed shown in Figure 2 indicates the general trends only. The cause of the scatter is as yet unknown.

This study is considered to be a very rough estimate of the effect of urbanization upon the flood hydrograph because the lack of hydrological data,

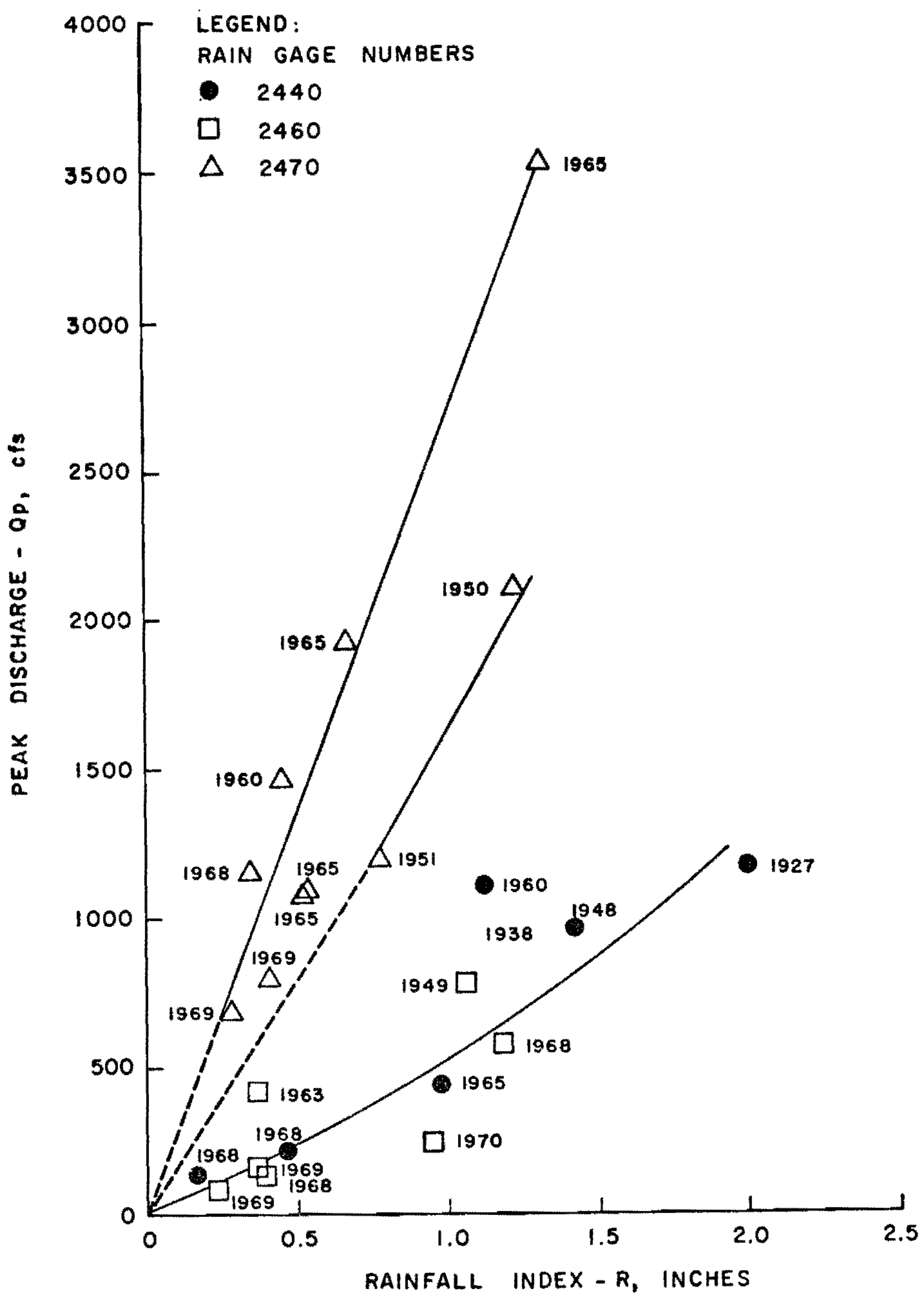

FIGURE 2. PEAK DISCHARGE - RAINFALL INDEX RELATIONSHIP FOR PALOLO WATERSHED.

such as evapotranspiration and soil-moisture, imposes great limitations. Continuous rainfall, runoff, evapotranspiration, and soil-moisture data are needed for a better flood hydrograph analysis for Oahu. Experimental watersheds have been developed for collecting data such as the runoff, the depth duration of a storm, the antecedent conditions of watershed soil-moisture content, evapotranspiration and infiltration data from the adjoined watersheds at St. Louis Heights and the Waahila Ridge, representing urban and natural watersheds, respectively.

INSTRUMENTATION OF THE URBAN AND NATURAL WATERSHEDS

One of the objectives of this project is the instrumentation of the adjoined St. Louis Heights and the Waahila watersheds.

A study of a topographic map revealed that the St. Louis Heights watershed is fully urbanized while the Waahila watershed remains relatively undeveloped. The exposure to the meteo-hydrological processes such as rainfall, wind, and sunshine of these two adjoined watersheds can be considered the same. The effect of man made changes on the watershed (changes from natural into urban) may be estimated by comparing the hydrographs from these two watersheds.

Description of an Urban Watershed: St. Louis Heights

The St. Louis Heights watershed lies in a southwest direction (Fig. 3). The main drainage outlet of this watershed is a 6' x 6' concrete box, which is also the outfall for Manoa Stream. The 6' x 6' outlet is located at an elevation of about 40 feet above mean sea level and the highest point of this watershed is about 1000 feet above mean sea level. The main axis of the watershed is about 7,130 feet long, its mean width is about 1000 feet, and the mean slope of the axis is about 15 percent.

The general topographic features of the St. Louis Heights watershed can be seen in Figure 3. The storm drainage system and its storm collection structures, such as the roadside gutters, storm collection basins, manholes and underground storm drainage pipe system, are separated from the sewerage. Most of the driveways to the dwellings in St. Louis Heights are directly connected to the storm drainage system. However, the percentage of other impervious areas in each lot which is connected to the storm drainage system has not been surveyed in detail.

The drainage area of the main storm drain in St. Louis Heights is much smaller than the watershed's topographic boundary because there are several sub-drainage systems to drain storm water to adjacent watersheds. The true

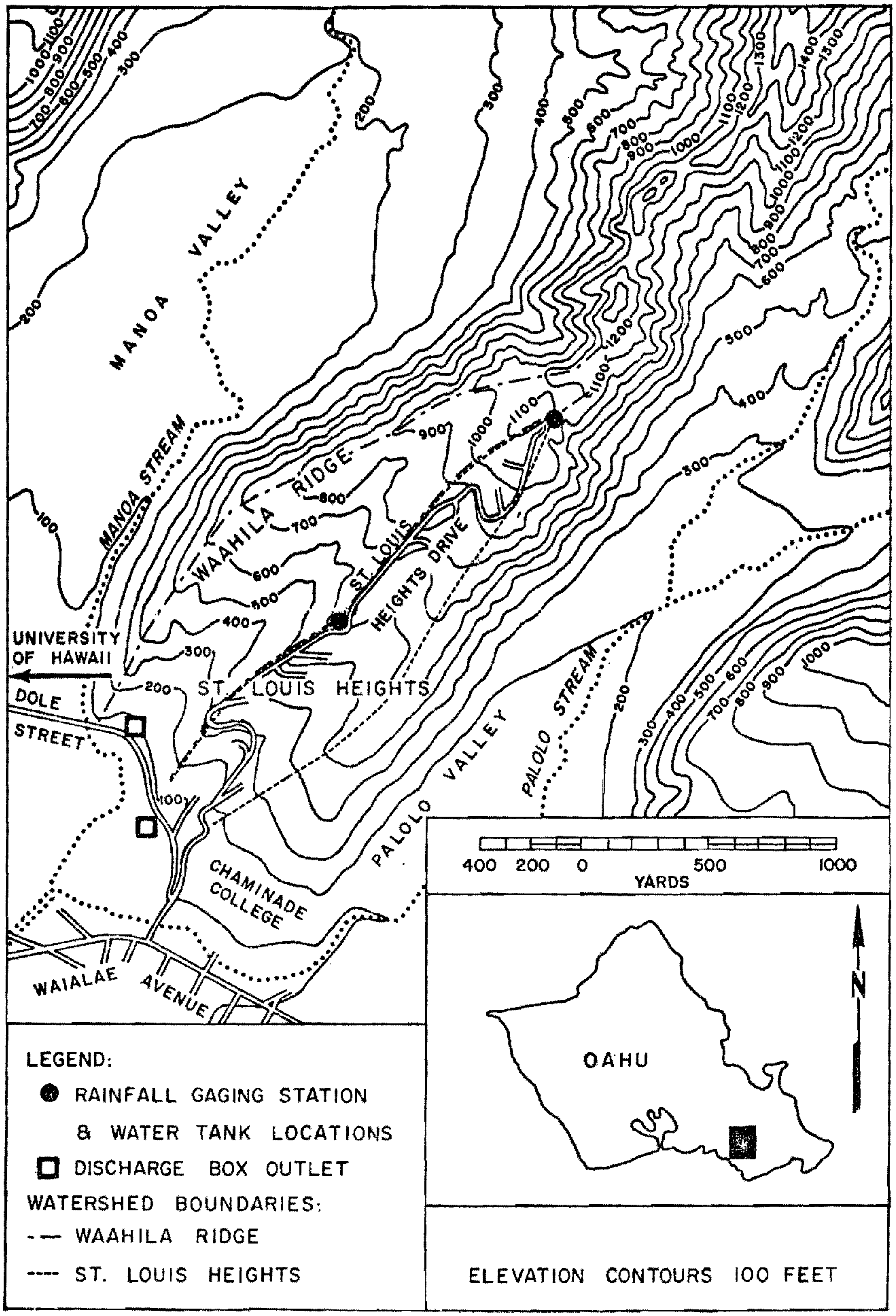

FIGURE 3. GENERAL LOCATION OF INSTRUMENTATIONS IN THE ST. LOUIS HEIGHTS AND WAAHILA RIDGE WATERSHEDS.

drainage boundary of the main storm drain can only be determined by field observations during heavy storms. Until a boundary is established, the drainage area of the main storm drain is estimated to be 99.5 acres. For the study of the rainfall-runoff relationship, because an accurate determination of the drainage area of the main storm drain is very important. A continuous streamflow stage recorder to monitor the runoff stage heights from this watershed has been installed downstream.

Sub-drainage systems which divert storm drain water from the St. Louis Heights watershed to the Waahila watershed have also been estimated.

Description of a Natural Watershed: Waahila Ridge

As shown in Figure 3, the geographical orientation of the Waahila Ridge watershed is almost the same as that for the St. Louis Heights watershed. The main discharge outlet for this watershed is also a 6' x 6' concrete box, which channels the runoff to the Manoa Stream. The elevation of the outlet is about 40 feet above mean sea level and the highest point of the watershed has an elevation of about 1100 feet. The main axis of the watershed is about 9000 feet long, the mean slope of the watershed is about 12 percent, and the mean width of the watershed is about 1500 feet.

Most of the Waahila watershed is covered with natural vegetation. Tall pine trees grow on about ten acres of the upper left portion of the watershed, which is part of the Waahila Ridge recreation area. At the lowest portion of the Waahila watershed, there are three University of Hawaii faculty apartment buildings which occupy about 10 acres. The total drainage area of the Waahila watershed is about 232 acres. If the area of the sub-drainage systems that drain water from the St. Louis Heights watershed were included, the total drainage area of the Waahila Ridge watershed would be about 250 acres.

The Installation and Maintenance of the Rain Gages

Two auto-recording, natural siphon rainfall recorders have been installed in the fenced-in water tank areas located along the Waahila-St. Louis Heights ridge as shown in Figure 3. One water tank is located at an elevation of about 1100 feet. The rain gage was installed on a leveled platform elevated two feet above the ground surface as shown in Figure 4.

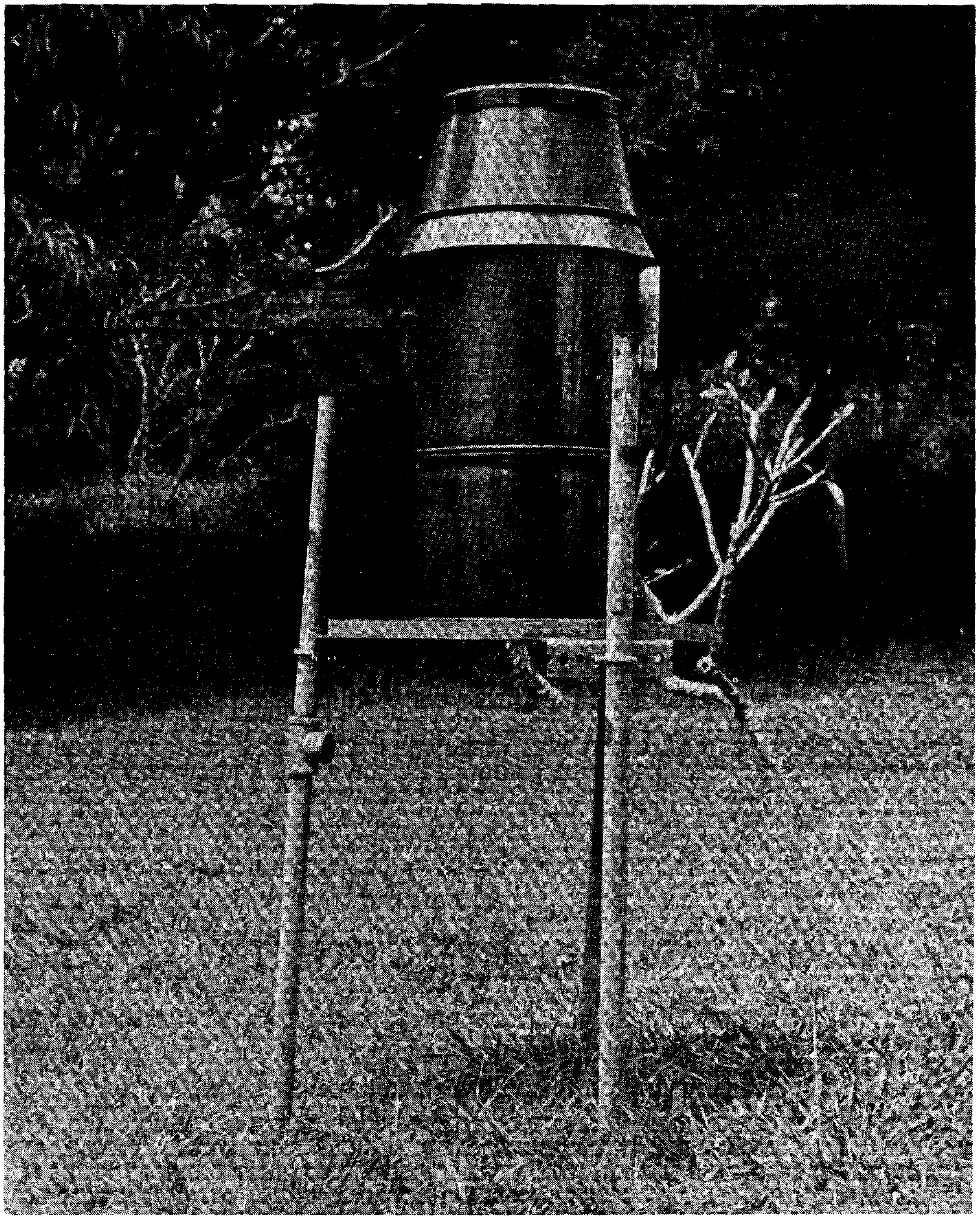

FIGURE 4. PICTURE SHOWS THE RAIN GAGE IN THE UPPER WATER TANK AREA IN ST. LOUIS HEIGHTS WATERSHED.

The second water tank is located at an elevation of about 600 feet. The rain gage has been installed on the southwest side of the water tank in an open area. Rain gage records have been kept on weekly basis since January 14, 1972.

The Installation and Maintenance of the Streamflow Gaging Stations

One streamflow stage auto-recorder was installed in the manhole located in the Kanewai Park (Fig. 5). This manhole is directly connected to the four-foot diameter main storm drain of the St. Louis Heights watershed. The stream stage recorder (shown in the inset in Fig. 5) is supported by a steel platform which is welded to a four-post truss. A 10-inch diameter thin-walled cylinder which serves as the stilling well for the float is also supported by the steel platform as shown in Figure 6. The open-ended PVC pipe to hold the counter-weight of the float, the supporting structure, and the hook-up of the 1/2 inch ϕ inlet copper tubing which feeds into the stilling well are shown in the inset in Figure 6. The instrumentation of the Waahila Ridge stream gaging station is similar to that in the St. Louis Heights watershed. However, the manhole which houses the stream stage recorder is connected indirectly by a 3-foot diameter concrete pipe to the 6 feet x 6 feet main storm drain of the Waahila Ridge watershed.

Because the main storm drains have steep slopes, the calibration of the stage-discharge relationships for both watersheds is a hydraulics problem which needs laboratory model studies. Although the flow conditions in both watersheds are super-critical (a condition caused by the very steep slope of the storm drain), the applicability of the velocity formulas such as Chezy's and Manning's formulas has yet to be determined. The streamflow stage hydrographs recorded in early 1972 were calibrated into discharges by Manning's formula and are shown in Appendix B.

INITIAL STUDIES OF THE WATERSHED SIMULATION MODELS

Auto-Optimal Method for Determining the Instantaneous Unit Hydrograph

In studying the effects of urbanization upon flood hydrographs from selected watersheds in Oahu, the availability of a continuous record of

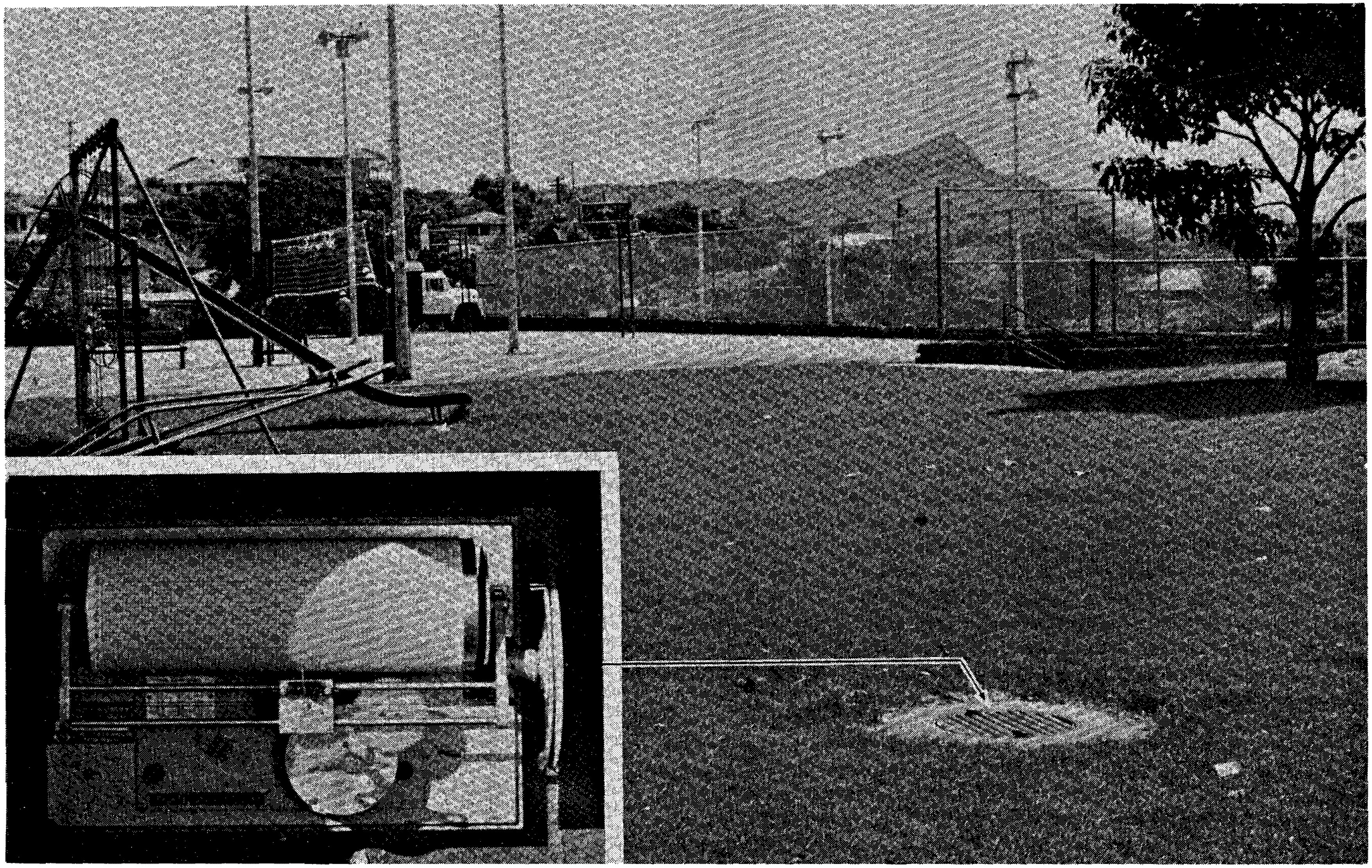

FIGURE 5. BACKGROUND SHOWS LOCATION OF THE MANHOLE IN THE KANEWAI PARK. THE INSET LOCATED IN THE MANHOLE.

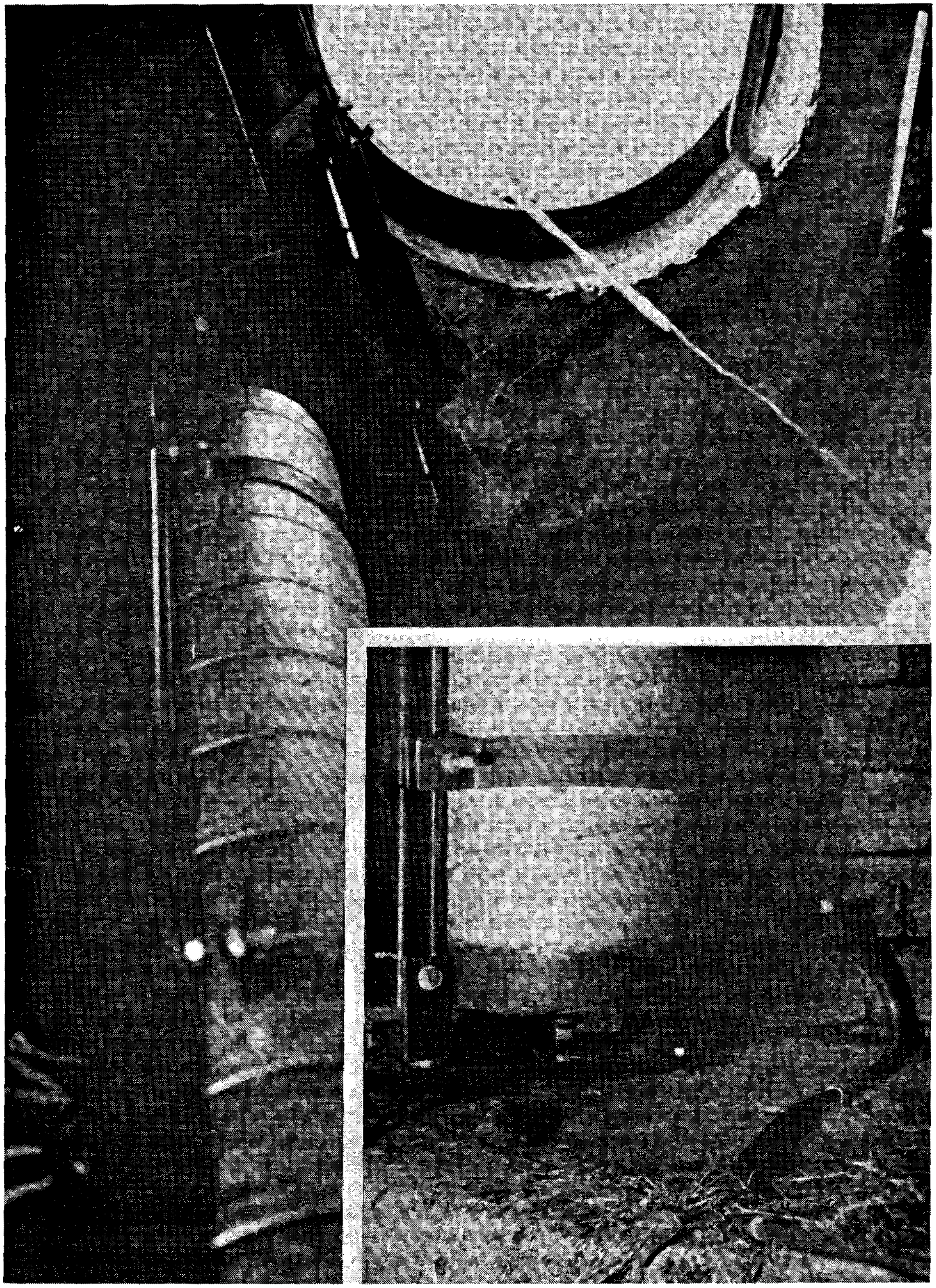

FIGURE 6. LIGHT FROM THE OPEN MANHOLE SHOWS THE 10-INCH THIN-WALLED CYLINDER WHICH IS THE STILLING WELL FOR THE FLOAT RECORDER. THE HOOK-UP TO THE 1/2" COPPER TUBING AND THE BASE OF THE STILLING WELL.

rainfall and streamflow is insufficient. Other data such as interception, evapotranspiration, infiltration, and soil-moisture content are needed because the antecedent conditions of the watershed and other hydrological characteristics also affect the hydrograph.

The simulation process for a watershed is initially a daily accounting of water budget of a watershed until there is a sufficiently large input of rainfall. Then the simulation process will switch to a minute or an hourly accounting-basis to simulate the response of the watershed so that detailed hydrologic reactions to such input can be evaluated.

Accordingly, the simulation of the hydrologic process in a watershed can be divided into two parts. The first part is the fair weather (slowly varying) hydrological process simulation for which the daily time unit is sufficient. The second part is the storm weather hydrological simulation which requires finer time units such as minutes.

Factors affecting the fair weather hydrological process are:

1. Size and shape of the watershed
2. Evapotranspiration and vegetative cover
3. Soil-moisture within the root zone and soil type
4. Position of water table and ground-water outflow
5. Rainfalls of low intensity and short duration which do not produce runoff

Factors affecting stormy weather hydrological process are:

1. Size and shape of the watershed
2. Rainfall intensity, duration, and distribution
3. Interception, depression storage, evapotranspiration, and infiltration
4. Overland flow and open-channel flow hydraulics
5. Stream network and stream morphological characteristics such as relief, slope, and length
6. Initial soil-moisture content in root zone, soil profile, soil type, and recharge to ground-water
7. Land-use and cover, urbanization and man-made storm drainage system

The above two hydrological processes may be studied separately or jointly. These are the concepts which guides the subsequent studies. Under the small and steep Hawaiian watershed conditions, the hydrograph from the stormy weather hydrological process has been identified as the flash flood type. Therefore, the study of rapidly varying hydrological process is more important.

Assuming that the hydrological processes of a watershed may be approximated by a linear hydrologic model, the hydrologic response of the watershed to a unit input of rainfall may also be reflected in the parameters of the instantaneous unit hydrograph (IUH). The parameters in the IUH equations may be estimated by simulating the daily soil-moisture in the watershed prior to a storm and by simulating the storm to determine the effective rainfall. This operation would involve the convolution summation of the sequence of effective rainfall and the impulse response function of the IUH. Optimal estimate of the IUH parameters may be obtained by an iterative process with the best estimate being the minimization of the sum of squares of the difference between the measured and computed runoff using several two-parameter IUH equations.

The objectives of the auto-optimal method in determining the parameters of the IUH that have been initiated are:

1. To write a soil-moisture loss accounting model using a simplified water-balance equation and to determine the effective precipitation of this model.
2. To determine which of the four two-parameter IUH equations would give the best transfer function for the selected natural watersheds monitored by U.S.G.S. stream gaging station nos. 2230, 2390, 2400, and 2460 and partially urbanized watersheds monitored by U.S.G.S. stream gaging station nos. 2293 and 2470 (see Fig. 7).
3. To obtain optimal estimates of the IUH parameters by an iterative process of fitting and diagnostic checks of the identified model.
4. To determine and define measurable urban parameters, which are assumed to be the most influential factors of the hydrologic system as reflected in the IUH model.
5. To determine the trend in changes of urban parameters from selected watersheds during 1952, 1960, 1965, and 1970.

Factors Involved in Hydrological Simulation

The procedures for this simulation study which have been programmed according to stormy weather hydrologic processes and the treatment of the

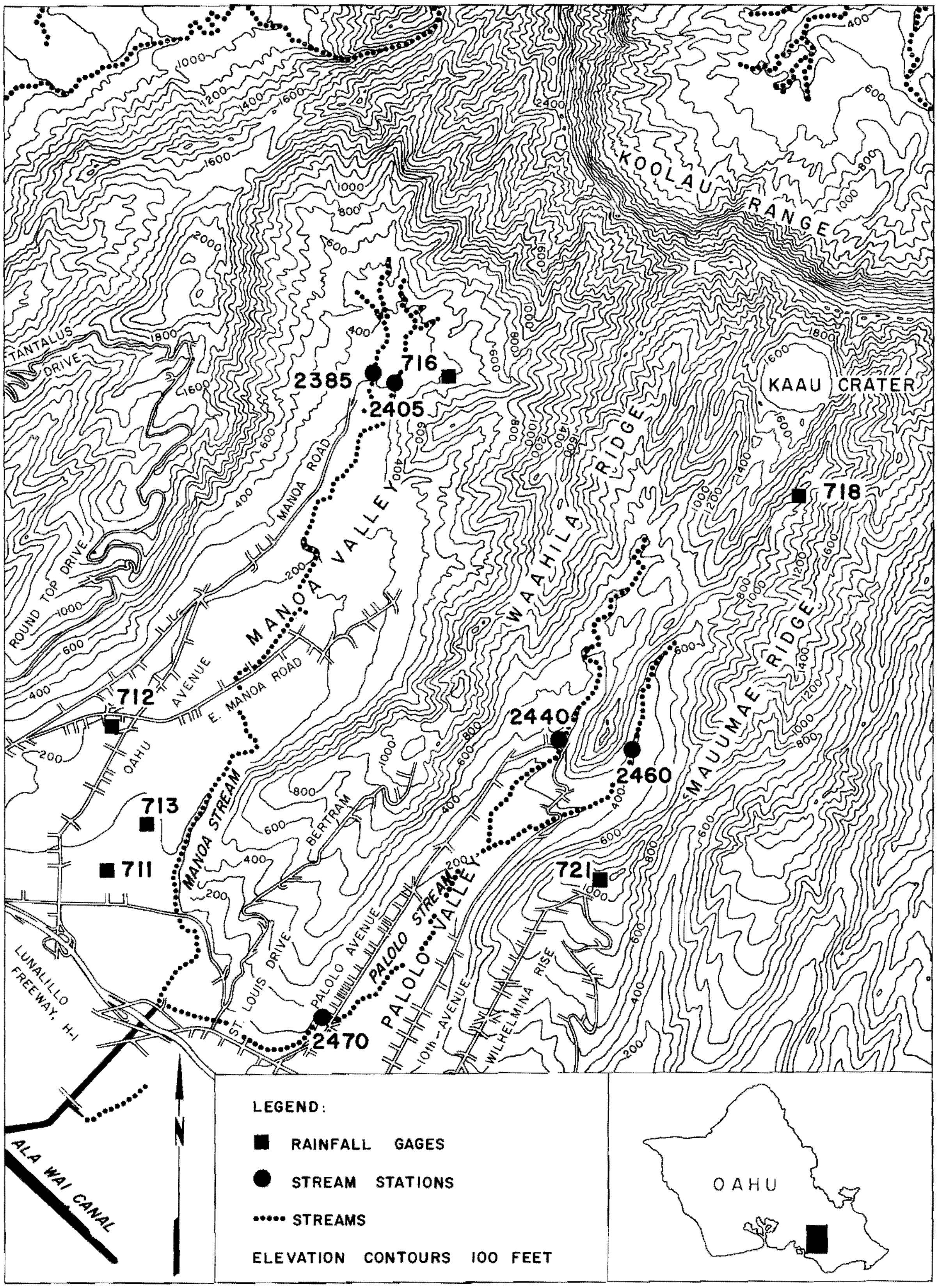

FIGURE 7. LOCATIONS OF RAIN GAGES IN AND NEAR PALOLO WATERSHED.

basic hydrological factors involved are discussed in detail below.

RAINFALL. According to Leopold, *et al.* (1951), the major factors that influence rainfall on Oahu are the winds, topographical barriers, and the temperature inversion. Therefore, the daily, monthly, and even yearly rainfall rates are not uniform over any given watershed. The analyses of rainfall data have led to the following decisions affecting methodology used for the current study:

(i) To study the non-uniformity of daily rainfall over a watershed.

(ii) To subdivide a watershed to obtain a more unifrom rainfall distribution in the sub-watersheds.

Daily rainfall data from rain gages within and near the boundaries of Palolo watershed were used. The rain gages involved in this study are Nos. 711.1, 712, 713, 716, 718 and 721 (the numbers are those of the National Weather Service rainfall gaging station serial). The locations of these rain gages are given in Fig. 7. Station 721 was selected as the control station because of its location in the study area. Daily rainfall greater than 1 inch from Station 721 were used as the basis upon which data from other stations were correlated. It was found that data from Station 718 were consistently higher than those from Station 721, while data from Station 711.1 were usually lower than those from Station 721. Hence, data from Station 718 were used as the input for upper Palolo watershed, and data from 711.1 were used as the input for lower Palolo watershed.

INTERCEPTION. In the forest area, part of the rainwater may be intercepted by the leaves and tree branches and be lost through evaporation. The report by Horton (1919) of his investigation on the interception of rainfall by vegetation can be summarized as follows:

(i) In comparing a tree in a forest and a tree in open space, the interception storage loss for a tree in a forest area is greater during a storm but the evaporation loss under the same conditions is less than for a tree in open space.

(ii) The interception losses range from 0.02 to 0.07 inches per storm.

(iii) Percent of interception loss is greater in light intensity shower than in heavy rainfall and may be high as 100 percent. When the intensity of storms is great and the duration is long, the percent of interception loss may be negligible.

Horton (1919) suggested an empirical equation for the estimation of interception as

$$I = 0.04 + 0.18P_s \tag{1}$$

where I = interception loss in inches

P_s = amount of precipitation per storm in inches

DEPRESSION STORAGE. Depression storage is the amount of rainfall retained in depressed surfaces in the watershed during and after a storm. This storm water is usually lost by evaporation and infiltration. In the latter case, the storm water may replenish the ground water or just increase the soil-moisture content in the soil profile. The volume of depression storage can be directly related to the slope of the watershed. As the slope increases, the amount of depression storage is decreased. The mean slopes of the Palolo watershed range from 0.035 to 0.15 ft/ft. The valley sides are even steeper, ranging from 40 to 70 percent or more than 70 percent in the upstream regions. Depression storage has been neglected in the watershed simulation process in this study because the depression storage is very small in comparison to other losses in its effect on runoff.

EVAPORATION AND EVAPOTRANSPIRATION. The study of evaporation from soil should include many factors, the most important of which is the variations of soil-moisture. When soil is saturated or the water table is near the soil surface, the evaporation from the soil surface may be close as that from free water surface. On the other hand, if the soil near the soil surface is very dry, evaporation may be retarded. Evapotranspiration involves the evaporation of water from soil and the transpiration of water from the soil and vegetation. Among the factors which affect the transpiration process is climate. Often the index of the potential transpiration of an area for hydrological analysis is provided by climate. Again, the evapotranspiration rate may be closely related to the soil-moisture content in the soil profile of a given watershed. The watersheds selected for this study contain natural and urban areas and there is no agricultural land involved.

According to Takasaki, *et al.* (1969), the evaluation of evapotranspiration in Hawaiian conditions may be based upon the following observed facts:

(i) Evapotranspiration is a function of rainfall and is not a "mean-monthly temperature" function.

(ii) Low evapotranspiration is measured in high rainfall areas.

(iii) High evapotranspiration is measured in low rainfall areas.

(iv) Evapotranspiration is closely correlated with evaporation pan measurement.

(v) Evapotranspiration is higher in windy areas.

(vi) Present evapotranspiration data are not sufficient for a detailed statistical analysis.

Ekern (1971) reported in a discussion of "Hydrology and Geology of Honolulu Aquifer" that in the marine climate of Hawaii, air temperature is almost independent of solar radiation; thus, a high correlation between temperature and evaporation does not exist. In another discussion, Ekern (1965) pointed out the failure of several temperature-based indices for estimation of pan evaporation in Hawaii. The annual rainfall has been shown as a convenient index for pan evaporation as well as evapotranspiration (Ekern 1966, 1970). Thus, the estimation of evapotranspiration loss for the watershed simulation model should be based on the soil moisture content and the monthly or annual rainfall.

INFILTRATION. Infiltration is an important hydrological process to describe the intake of water into the soil. The amount of water infiltrating into the soil is determined by the hydraulic conductivity of the soil, the initial soil-moisture content, the porosity of the soil, and the capillary potential of the soil. Holtan's infiltration equation (Holtan, 1961) is expressed as

$$f = fc + A\ (S_o - F)^B \tag{2}$$

in which f = infiltration rate, L/T

f_c = infiltration capacity which is the infiltration rate that approaches a constant, L/T

S_o = available porosity at the beginning of the storm

F = accumulative infiltration soil water content in volume basis

A and B = constants

Holtan considered the infiltration rate to be a function of the remaining void volume in the soil profile above a confined horizon and the permeability of the soil profile. The advantage of Holtan's infiltration equation is that the equation is not expressed as an explicit function of time. Therefore, it is very useful for evaluating infiltration under intermittent rainfall conditions. When it rains, the potential infiltration rate decreases as the accumulative infiltration level increases as expressed in

Equation (2). When the rain stops, part of the accumulated infiltration water will be drained and thus the potential porosity to store more water is increased when it rains again. Huggins and Monke (1968) suggested three methods to compute the drainage process during infiltration. When the soil-moisture is less than field capacity, the drainage rate is considered to be zero. When the soil is saturated, the drainage rate equals the constant infiltration rate. When the soil-moisture is between saturation and field capacity, the drainage rate D is a function of constant infiltration rate f_c, unsaturated pore volume P_u, and the maximum pore volume G, as expressed in Equation (3).

$$D = f_c \left[1 - \frac{P_u}{G}\right] \tag{3}$$

In this simulation study, the effective rainfall is defined as that fraction of rainfall remaining after all available pore space in the soil profile has been filled up by water.

Equation (2) is integrable only when the values of B are integers. Overton (1964) suggested that B = 2 and the values of A be determined by plotting $(f-f_c)$ versus $(S_o-F)^2$.

The antecedent soil-moisture content before a storm has a very important effect on the flood hydrograph which is closely related to the soil type in the watershed. In the infiltration process study, it is pointed out that the soil-moisture content is considered in this study. The treatment of soil-moisture in the simulation watershed is discussed under "Soil-moisture accounting," (p. 26) and will not be repeated here.

OVERLAND FLOW AND CHANNEL FLOW HYDRAULICS. As indicated before, Hawaiian small watersheds have very short and steep streams. According to Wu (1969), the time to peak in the hydrographs from 27 of the 29 watersheds he studied ranged from 15 to 90 minutes. The very short duration of the flood is one of the characteristics of Hawaiian flood hydrology, hence, the fluid mechanics of overland flow and the open channel flows has not been made in this study.

STREAM SYSTEM AND STREAM MORPHOLOGICAL CHARACTERISTICS. The composition of the stream systems and the morphological characteristics of the streams, such as the relief, slope, and length, in a watershed influence the flood peak in a statistical multiple regression study (Wu, 1967). However, since the current study follows the instantaneous unit hydrograph theory, the approaches do not include any physical properties of streams.

LAND USE AND COVER, URBANIZATION, AND MAN-MADE DRAINAGE SYSTEM. The classification of land use in a watershed is a very useful input for the simulation of a watershed because it reflects the effects of man's influence upon the watershed.

Forest and brushland dominate the steep mountainside in the upper reaches of the Palolo watershed. In these areas, slopes are gerater than 40 percent and gulches and narrow ridges are very common. The soils, which overlie soft bedrock, are only a few inches in depth, according to a report by the Soil Conservation Service (1970).

Most of the natural topographical changes occur slowly and gradually. Therefore, the influence of topographic changes on the shape of the hydrograph may be evaluated in terms of several years. However, there is no report of any natural change in the topography of the Palolo watershed for the past several decades. Thus, any variations in the IUH parameters may be attributed to urbanization.

The major effects of urbanization on a watershed are increases in impermeable area, leveling of the land for buildings, changes in the natural surface drainage system patterns because of streets and roads, installation of a storm drainage system, and removal of natural land cover. Attempts were made to relate the urban-related factors to four different forms of two-parameter IUH's and to evaluate the best representative two-parameter IUG among the four for further study. The urban-related factors are:

(i) Percentage of urban area, PUA, defined as

$$\text{PUA} = \frac{\text{urbanized area}}{\text{total watershed area}} \; 100\%$$

(ii) Impervious Length Factor is defined by Riley and Narayama (1968) as the ratio of the mean length of travel between the center of a particular impervious area and the discharge measuring point to the maximum length of travel in the watershed

(iii) Storm drainage density

(iv) Number of dwellings per unit area

These characteristic of urbanization have been evaluated from aerial photographs, topographical maps, sewer drainage maps, and storm drainage maps from the City and County of Honolulu for the periods 1952, 1965, and 1969.

Formulation of the Simulation Model

WATER-BALANCE EQUATION. The soil-moisture content in a watershed may be simulated to account for the antecedent conditions which prevails before a storm for the evaluation of effective rainfall and the subsequent runoff. A water-balance equation is presented as

$$\text{Runoff} = \text{Rainfall} - \text{Losses}$$

in which the losses include interception storage IS, depression water storage DWS, evapotranspiration ET, infiltration F, and ground water storage GWS. The interception storage may be considered as delayed evaporation and the depression water storage may be associated with infiltration. The infiltration can be directly related to runoff during and immediately after the storm. Therefore, in a given time interval Δt, the water balance equation can be written as:

$$P = Q + ET + \Delta S \qquad (4)$$

in which P = rainfall, Q = runoff, S = summation of storages, ΔS = change in total storage within Δt, and S = DWS + IS + GWS.

SOIL-MOISTURE ACCOUNTING. According to the previous discussion, the accounting of soil moisture should follow the two kinds of weather conditions, *i.e.*, fair weather and stormy weather conditions. During a fair weather period, soil moisture SM is observed or simulated on a daily basis (Δt=24 hours) and may be extended for several days after a storm. During a stormy weather period, the soil moisture is measured on an hourly basis and may be shortened for less than one hour to a few minutes.

Accounting for drying period (fair weather). Two approaches to account for soil moisture have been considered. The first approach is daily accounting. When soil moisture is less than saturation and more than field capacity, then soil moisture can be estimated as follows:

$$SM_j = SM_{j-1} - AcET_j - G_j \qquad (5)$$

in which SM_j = soil moisture j days after a storm, $AcET_j$ = actual evapotranspiration on the jth day, AcET is a function of Potential ET and SM, and G_j = deep seepage loss the jth day.

When the soil moisture is less than or equal to field capacity G_j = 0, Equation (5) is reduced to

$$SM_j = SM_{j-1} - AcET_j \qquad (6)$$

The second approach may be used in the absence of adequate data to compute the potential evapotranspiration. This second approach allows the accounting of SM_j during a no-rain period. The depletion of soil moisture by evapotranspiration may be represented by

$$SM_j = (SM_o)k^j \qquad (7)$$

in which SM_o = initial soil moisture at the start of the accounting period and k = a depletion constant which may be considered as a constant throughout the year in forested areas or determined monthly to reflect seasonal changes. K is affected by factors inducing evapotranspiration.

Accounting for rain period (stormy weather). During the rain period, the effective rainfall that produces runoff may be estimated when the rainfall rate P is greater than the infiltration rate f. However, the interception loss should be accounted for but the evapotranspiration loss can be neglected. In forested areas, the runoff may be greatly delayed because of the interception loss, while in urbanized areas, the runoff may begin sooner because of the impervious areas. The following equations are used to evaluate effective rainfall R during the Lth interval:

$$R_L = R_{UL} + P_L - f_L \qquad \text{when } P>f \qquad (8)$$

$$R_L = R_{UL} \qquad \text{when } P<f \qquad (9)$$

$$R_L = 0 \qquad \text{when } P = 0 \qquad (10)$$

in which $R_{UL} = cP_L$ and c = an urban runoff coefficient.

THE KENTUCKY WATERSHED MODEL

The Kentucky Watershed Model (KWM) is a comprehensive watershed simulation model which was translated and expanded from Stanford Watershed Model (SWM) by James (1970). The KWM inherited comprehensiveness from the SWM and has two main programs and twenty subroutines which include approximately 560 parameters and more than three thousand statements.

The main tasks with KWM in this project is to rewrite or modify the KWM computer programs and subroutines to suit Hawaiian hydrological conditions, to test the applicability of the modified KWM, and to determine the sensitivity of the 560 parameters considered in the modified KWM through test runs on a digital computer.

Hydrological data from the Kalihi watershed were compiled and interpreted for test runs on the modified KWM. Hourly rainfall and streamflow data from the water year 1964 have been used for the test runs. Preliminary results indicate that the modified KWM is working although the simulated daily stream flow is not very encouraging. The discrepancy between measured and simulated daily streamflow can be reduced by further modifying the physical processes of the parameters considered in the modified KWM because most of these physical processes are empirical evaluations.

CONCLUSIONS

The following are preliminary conclusions based on the first phase of this study:

1. To aim at a better understanding of the flood hydrology on Oahu, this report examines the causes and characteristics of storm flood occurred on Oahu as related to the progress of urbanization.

2. Most urbanized watersheds on Oahu have experienced a period of frequent floods during their developmental stage. In time, based on previous experience and improvements of the flood prevention systems, these watersheds generally reduced the frequency of floods.

3. Both Honolulu, an urbanized district, and Waialua, an agricultural district, reported more floods than any other area on Oahu. Because Honolulu is spread over a large area and it is highly urbanized, the probability of floods caused by heavy storms is much greater than in Waialua. On the other hand, Waialua is situated downstream from an irrigation canal and several large streams. An overflow from the irrigation canal or the streams will result in a flood in Waialua.

4. Based on the study of the Palolo and Kalihi watersheds, the effects of urbanization can be tentatively summarized as having a twofold influence on flood hydrographs: (1) urbanization increases the flood peak and (2) urbanization shortens the time to peak. However, more hydrologic data are needed to confirm this observation.

5. The instrumentation at the St. Louis Heights and the Waahila Ridge watersheds is a long term hydrological data collection effort. The effects

of urbanization on flood hydrographs can be evaluated by a comparison of the hydrographs from these two watersheds.

6. The initial results of the watershed simulation model study are very promising. The auto-optimal method for determining the characteristics of the instantaneous unit hydrograph is usable. Modifications of the Kentucky Watershed Model has been initiated and will be continued during the second phase of this study.

ACKNOWLEDGMENTS

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APPENDICES

APPENDIX A

APPENDIX A. DEPARTMENT OF LAND AND NATURAL RESOURCES FLOOD DRAINAGE SURVEY FORM.

FLOOD DAMAGE SURVEY

Survey by:______________________ Date of Survey:____________________

Stream or Area:__________________ Date(s) of Flood:__________________

1. NATURE AND CAUSE OF FLOOD (Check applicable space)

   a. Heavy rainfall ____
   b. Flash flood ____
   c. Hurricane ____
   d. Abnormal tide ____
   e. Tsunami ____
   f. Others (specify)____
   ____

   (Do not fill in space)

   Rainfall, inches

   Gaging station(s)____________________
   Min. per 24 hrs. & date_______________
   Max. per 24 hrs. & date_______________
   Average during storm_________________
   TOTAL DURING STORM__________________

2. EXTENT OF FLOODING

   a. If map is available, plot maximum limits of flooded area.
   b. If map is not available, reference maximum limits of flooded area to fixed markers and record on Section 9 of this form.
   Example: 50 feet west of power pole No. 10.

3. RESIDENTIAL PROPERTY DAMAGE

   a. Maximum depth of floodwater

Outside building:	Yes____	No____	Depth________inches
Inside building:	Yes____	No____	Depth________inches
Basement:	Yes____	No____	Depth________inches

   b. Value of property

   No. and Market Value of Buildings

___ @ Less than - $ 5,000	___ @ $27,500 - $29,999
___ @ $ 5,000 - 7,499	___ @ 30,000 - 32,499
___ @ 7,500 - 9,999	___ @ 32,500 - 34,999
___ @ 10,000 - 12,499	___ @ 35,000 - 37,499
___ @ 12,500 - 14,999	___ @ 37,500 - 39,999
___ @ 15,000 - 17,499	___ @ 40,000 - 42,499
___ @ 17,500 - 19,999	___ @ 42,500 - 44,999
___ @ 20,000 - 22,499	___ @ 45,000 - 47,499
___ @ 22,500 - 24,999	___ @ 47,500 - 49,999
___ @ 25,000 - 27,499	___ @ 50,000 - Over

   Estimated @ ______________
   Estimated @ ______________
   Estimated @ ______________

No. and Market Value of Contents

___ @ Less than - $ 500	___ @ $5,000 - $5,499
___ @ $ - 999	___ @ 5,500 - 5,999
___ @ 1,000 - 1,499	___ @ 6,000 - 6,499
___ @ 1,500 - 1,999	___ @ 6,600 - 6,999
___ @ 2,000 - 2,499	___ @ 7,000 - 7,499
___ @ 2,500 - 2,999	___ @ 7,500 - 7,999
___ @ 3,000 - 3,499	___ @ 8,000 - 8,499
___ @ 3,500 - 3,999	___ @ 8,500 - 8,999
___ @ 4,000 - 4,499	___ @ 9,000 - 9,499
___ @ 4,500 - 4,999	___ @ 9,500 - 9,999

Estimated @ ___________
Estimated @ ___________
Estimated @ ___________

Total residences demolished ___________________
Total residences damaged ___________________

c. Estimated flood water damage losses, repair or replacement cost

	Total Damages	Sediment Damages Only
Residence buildings		
First floor: foundation, wells, floors, wiring, etc.	$_______	$_______
Basement: walls, floors, etc.	$_______	$_______
Residence contents: furniture, equipment, appliances, cars, personal belongings	$_______	$_______
Residence lot improvements: Lawns, trees, fences, etc.	$_______	$_______
Other losses: cleaning up, emergency measures, evacuation, etc.	$_______	$_______

d. Remarks: ____

____

____

____

____

4. COMMERCIAL AND INDUSTRIAL PROPERTY DAMAGE

a. Maximum depth of flood water

Outside building:	Yes ____	No ____	Depth ____	inches
Inside building:	Yes ____	No ____	Depth ____	inches
Basement:	Yes ____	No ____	Depth ____	inches
Over yard or lot:	Yes ____	No ____	Depth ____	inches

b.

Value of property	$ ____
Market value of structure	$ ____
Market value of fixtures owned by landlord	$ ____
Market value of equipment	$ ____
Market value of merchandise stocks	$ ____
Total market value of fixtures, equipment and stocks	$ ____

c. Estimated flood water damage losses, repair or replacement cost

	Total Damages	Sediment Damages Only
Lot improvements: lawns, trees, fences, etc.	$ ____	$ ____
Structure: foundation, walls, floors, wiring, etc.		
First floor	$ ____	$ ____
Basement	$ ____	$ ____
Contents: furniture, equipment, fixtures, furnishings, merchandise stocks		
First floor	$ ____	$ ____
Basement	$ ____	$ ____
Other direct damages: debris and sediment cleanup cost, flood-fighting and lifesaving, improving health hazard, etc.	$ ____	$ ____
Indirect damages		
Business income loss	$ ____	$ ____
Employee wages loss	$ ____	$ ____
Others: evacuation and reoccupation loss, flood prevention work, flood relief, etc.	$ ____	$ ____

d. Remarks: ____________________

____

5. PUBLIC UTILITIES DAMAGE

a. Name of highway or street flooded: ____________________

Maximum depth of water: ____________ feet

Duration highway or street flooded: ______ days ________ hours

Maximum depth of sediment: ____________ inches

Existence of highway or street drainage where flooded:

Yes ______ No ______

If yes, type of facilities installed:

1. _____ barrels _____ inch diameter pipe
2. _____ barrels _____ inch diameter pipe
3. _____ inch wide by _____ inch high box culvert
4. _____ inch wide by _____ inch high box culvert

Physical condition of facilities

Before flood: Clogged? ___ Partially clogged? ___ Clear? ___
During flood: Clogged? ___ Partially clogged? ___ Clear? ___
After flood: Clogged? ___ Partially clogged? ___ Clear? ___

b. Others: utility lines, sewers, water, gas, etc. ____________________

c. Remarks:

6. HEALTH HAZARD

a. Did cesspool(s) overflow? Yes ___ No ___ If yes, how many ________

Did sanitary waste "back up" and flood basement or ground floor? Yes ___ No ___ If yes, how many ____________

Longest number of days cesspool(s) inoperative: ________ days

b. Did stagnant pool(s) form? Yes ___ No _____

Longest number of days standing: ______ days

c. Remarks: ____________________

7. CASUALTIES

A. Human lives: _____ lost _____ missing _____ injured

Details: ____

____

b. Domestic animals: _____ lost _____ missing _____ injured

Details: ____

____

c. Remarks: ____

____

____

____

8. CROP DAMAGE

Type	Total Damages	Sediment Damages Only	Approx. Area
____________	$ ________	$ ________	________ acres
____________	$ ________	$ ________	________ acres
____________	$ ________	$ ________	________ acres
____________	$ ________	$ ________	________ acres
____________	$ ________	$ ________	________ acres
____________	$ ________	$ ________	________ acres

9. MISCELLANEOUS

Remarks and details: ____

____

____

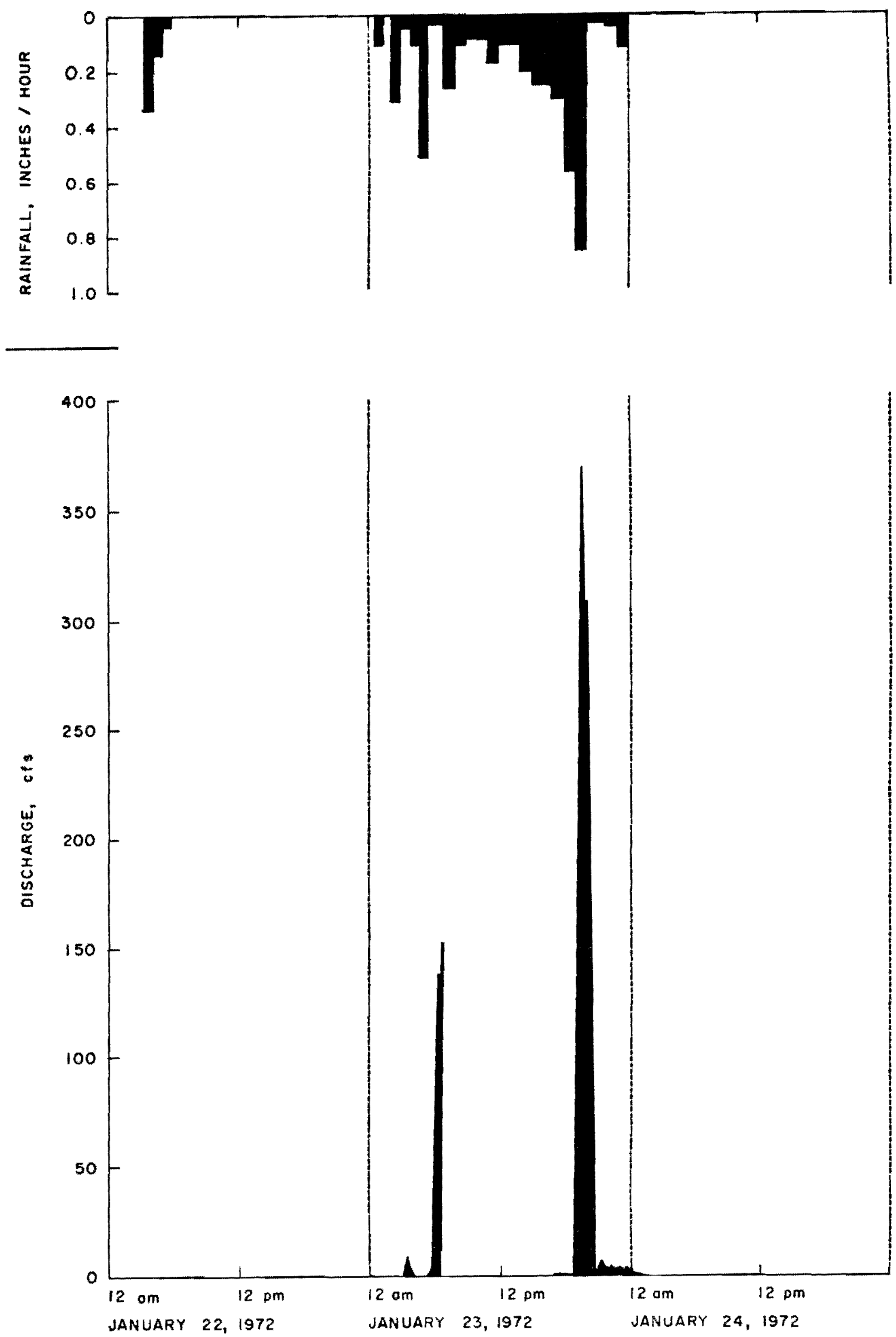
____

____

____

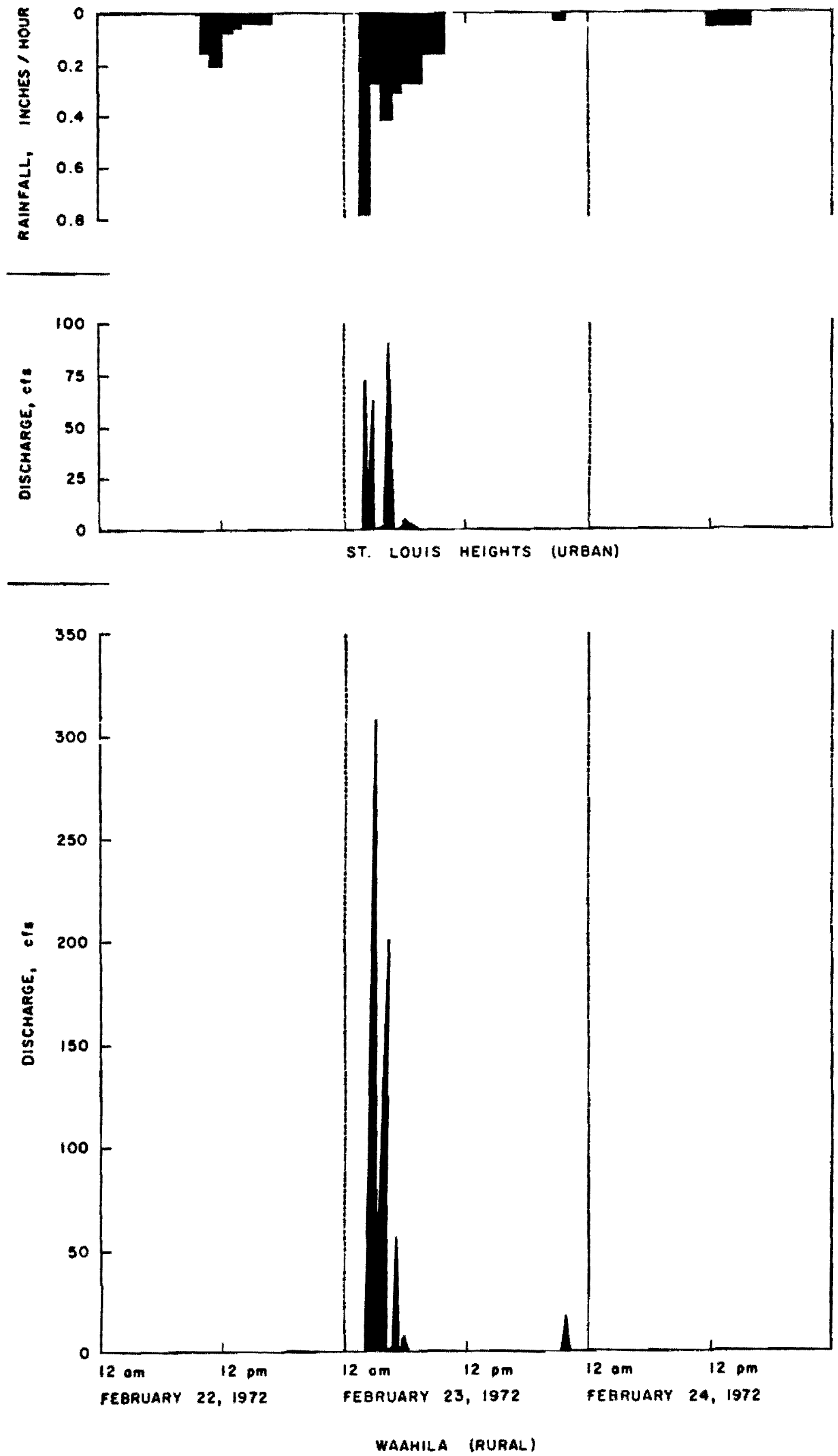
APPENDIX B

APPENDIX B.1. STORM FLOOD HYDROGRAPH, JANUARY 23-24, 1972.



ST. LOUIS HEIGHTS (URBAN)

APPENDIX B.2. STORM FLOOD HYDROGRAPH, FEBRUARY 23, 1972.



APPENDIX B.3. STORM FLOOD HYDROGRAPH, APRIL 3, 1972.