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Hawaiian Alpine Lake Level, Rainfall Trends, and Spring Flow[1]

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ABSTRACT: During the period May 1965 to November 1978 (162 months) 127 measurements were made of Lake Waiau water levels and overflow. This small perched body of water is located in Puu Waiau crater, at about 3970-m altitude, near the summit of the dormant volcano, Mauna Kea, Hawaii. Differences in water level are compared to the Hawaii statewide rainfall index, and to Waihu Spring flow. It is suggested that lake level is a useful indicator of rainfall trends among the islands.

Measurements of the tritium concentrations of Puu Waiau crater perched lake and groundwaters, and of the nearby spring waters on the south slopes of Mauna Kea, are used to indicate that seepage from the lake is probably the principal spring-water source during drought periods. The tritium measurements suggest that something blocks direct groundwater seepage out of the Waiau crater, and indications are that the blockage is ice in a subsurface layer of relict permafrost.

Study of the changes in lake and groundwater levels during the 30-month dry period July 1976 to December 1978 indicates that the groundwater basin probably occupies almost the entire Waiau crater catchment area (i.e., $\sim 10^5$ m^2).

It is suggested that permanent water-level and overflow gauges be established at Lake Waiau, and that long-term records from these gauges would be climatologically and hydrologically useful.

LAKE WAIAU is a small body of perched water in the crater of Puu Waiau, a cinder cone near the summit of the volcano Mauna Kea, at about 3970-m altitude (Figure 1). It is exposed to the dry atmosphere far above the tradewind inversion (Jefferies and McKnight 1968), and is thought to be formed by drainage of precipitation from within Puu Waiau crater (Gregory and Wentworth 1937). The lake and associated groundwaters around it are apparently perched there by a layer of fine sediment of local and perhaps continental eolian origin (Woodcock and Groves 1969; Sridhar et al. 1978), as well as by deeper fines of hydrothermal origin produced when Puu Waiau was formed, probably in the presence of an ice cap (Ugolini 1974).

Over a period of about 14 years I have made many diverse observations concerning Lake Waiau (LW) and its environment, some of which have been published (Woodcock 1974; Woodcock and Friedman 1979; Woodcock and Groves 1969; Woodcock, Rubin, and Duce 1966). On each field trip to the summit area to make the observations required in the above published work, I also made as many additional observations of other interesting phenomena as the time and my energy allowed.

Among the numerous unpublished observations are those of LW water levels and overflow amounts, and of Puu Waiau (PW) perched groundwater levels. The long drought of the 1976 to 1978 period added to the usefulness of these observations. My purpose here is to present these and other

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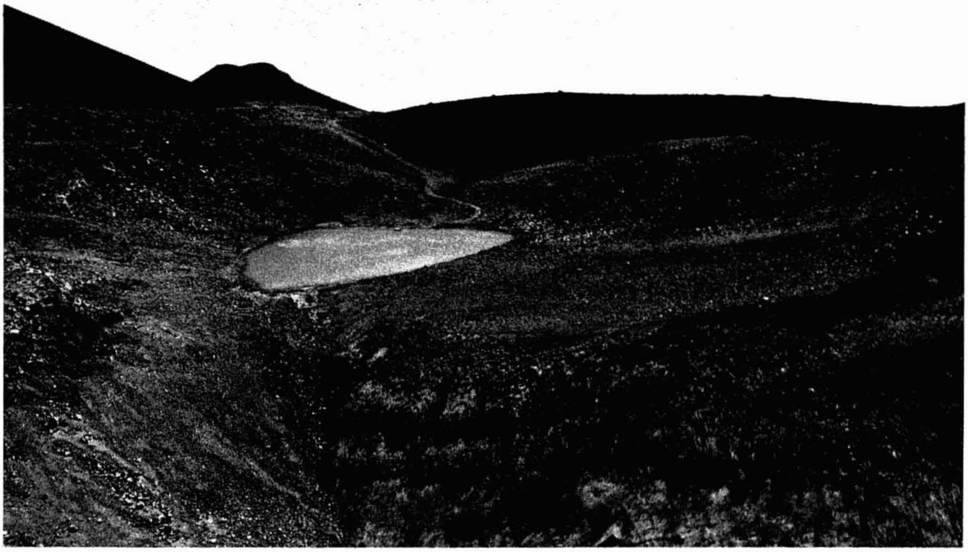

FIGURE 1. View of Lake Waiau and Puu Waiau crater, October 1968, looking eastward from over the head of Pohakuloa Gulch. The gulch originates at the breach in the west side of the Waiau crater cone (photo, left foreground, and Figure 5) through which lake overflow occurs. The top of Puu Lilinoe and the base of Puu Hau Kea are seen in the distance at the left. Photo by A. T. Abbott.

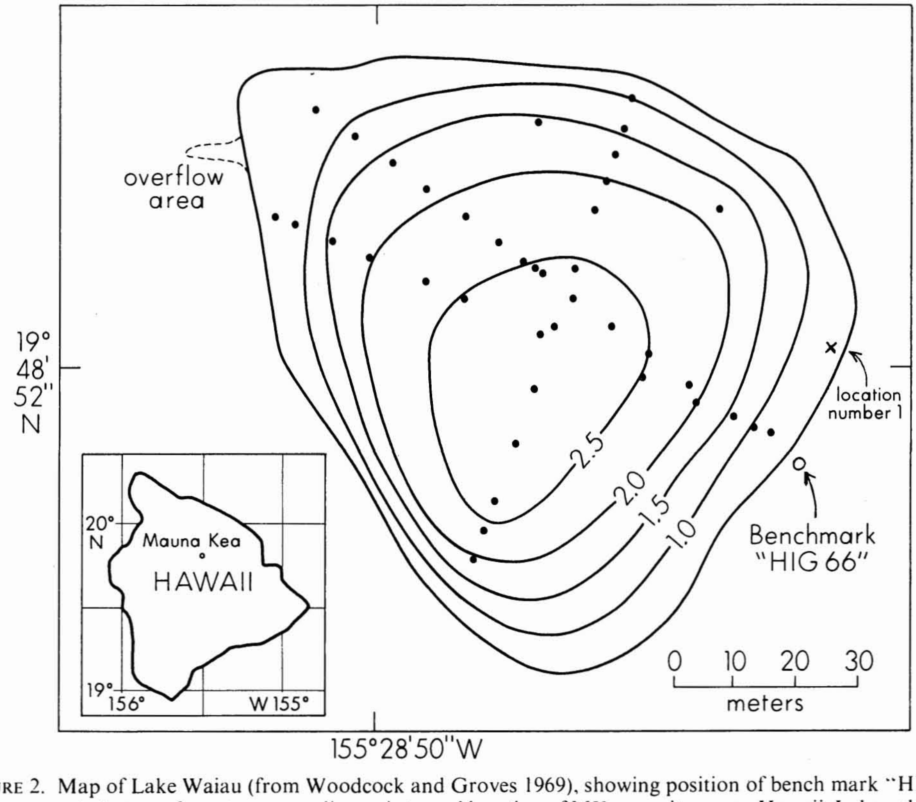

FIGURE 2. Map of Lake Waiau (from Woodcock and Groves 1969), showing position of bench mark "HIG '66," depth contours (m) at overflow stage, sounding points, and location of MK summit area on Hawaii. Lake volume and area, based on these contours, estimated to be $\sim 11{,}600$ m^3 and $\sim 6{,}810$ m^2.

pertinent observations, and to discuss their apparent relationships to Hawaiian rainfall trends and to the Mauna Kea (MK) climate and spring flow. I believe that the results also will be useful, eventually, in studies of the wet and dry periods in the Hawaiian climate.

MEASUREMENTS

Lake levels were measured each 1.3 months, on the average. Reference level was a bronze bench mark (BM) near the east shore (Figure 2, bench mark "HIG '66"). The mark is embedded in a 15-cm-diameter concrete pier set 1.2 m in the ground. The top is about even with the ground surface, and is usually from 15 to 25 cm above lake level at overflow stage. All lake levels are presented in cm below the bench mark (e.g., Figures 3 and 4).

During periods of overflow and when ice and snow did not interfere too much, the overflow rates were measured at a small waterfall about 30 m from the lake in the outflow channel (see Figures 1 and 2) with volumetric containers and a stopwatch. These rates did not exceed about 1.9 l sec^{-1} (i.e., ~ 164 m^3 day^{-1}; see Table 1).

Relative lake and groundwater levels were usually measured with a 20-m-long, water-filled, flexible tube of 0.8-cm inside diameter. One end of the tube was attached to a stake driven beside the lake, and the other end was then attached successively to stakes beside holes dug to groundwater depths at various distances inland from the shore (e.g., Figures 6 and 7). The difference between lake level and groundwater levels was then simply the distance of lake level below water level in the tube at the lake end, minus the distance of the groundwater level below the tube-water level at the hole ends. After the holes were dug, adequate time was allowed for groundwater level to reach equilibrium before relative levels were measured. The reproducibility among measurements of relative level found by this method was ± 0.4 cm. Lake and bench mark levels were also measured by the tube method.

TABLE 1

DATES AND RATES OF LAKE WAIAU OVERFLOW DURING THE PERIOD MAY 1965 TO MAY 1976 (FIGURE 3), AND THE AVERAGE WAIHU SPRING FLOW, ON THE SAME DATES, BETWEEN JUNE 1969 AND MAY 1976 (LOWER CURVE, FIGURE 4)

DATE	OVERFLOW m^3 day^{-1}	SPRING FLOW m^3 day^{-1}	RATIOS
30 May 1965	27.0		
19 Mar 1966	6.9		
5 Jan 1967	2.9		
5 Feb 1967	27.7		
3 Mar 1967	12.3		
8 Apr 1967	51.7		
4 May 1967	11.5		
25 Jul 1967	24.4		
8 Aug 1967	6.5		
20 Sep 1967	0.5		
5 Dec 1967	11.9		
15 Jun 1968	51.9		
10 Jul 1968	1.7		
18 Oct 1968	2.6		
9 Nov 1968	0.7		
2 Jan 1969	28.8		
16 May 1969	12.9		
26 Jun 1969	0.3	225	0.00
15 Apr 1971	90.6	177	0.51
31 May 1971	56.9	185	0.31
18 Jun 1971	17.3	159	0.11
19 Jul 1971	2.9	100	0.03
22 Feb 1972	74.0	250	0.30
18 Mar 1972	51.9	271	0.19
26 Apr 1972	39.8	274	0.15
25 May 1972	1.8	159	0.01
5 Jan 1974	64.0	216	0.30
4 Mar 1974	28.8	236	0.12
2 Apr 1974	27.3	194	0.14
29 Apr 1974	20.3	185	0.11
25 Apr 1975	159.0	200	0.80
5 Jun 1975	47.1	142	0.33
7 May 1976	164.0	129	1.26
Averages (June 1969 to May 1976 only)	52.8	194	0.27

Waihu Spring flow has been metered and recorded daily since 1969 by the U.S. Army Engineers. The flow data were made available to me by the Utilities Division, U.S. Army Support Command, Building 344, Fort Shafter, Honolulu, Hawaii. The spring flow originates at Liloe, Waihu, and Hopukani Springs (altitudes 2720, 3000, and 3190 m, respectively), just west of Pohakuloa Gulch

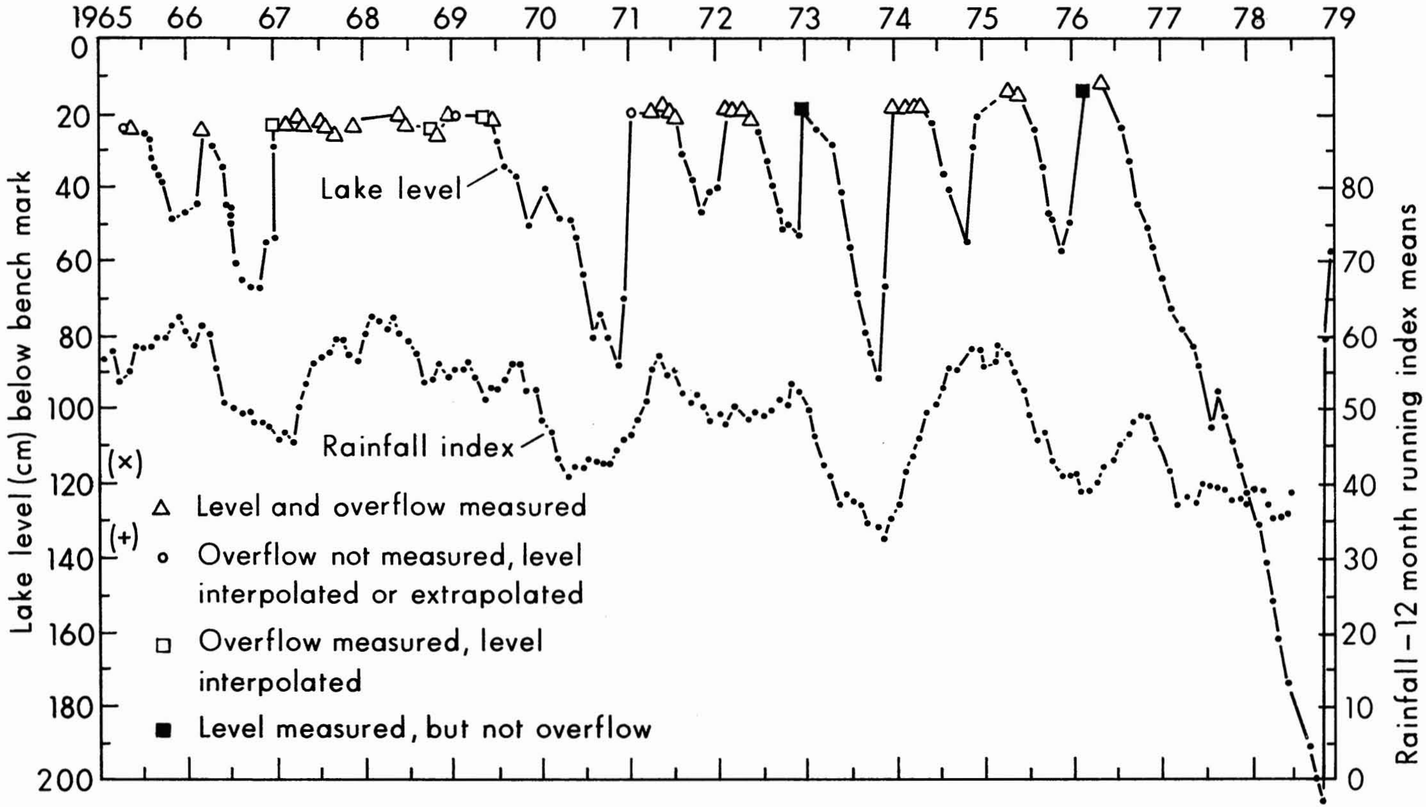

FIGURE 3. Lake level and Hawaiian rainfall index, 1965 to 1978. On upper curve the dots show distance of lake surface below bench mark at times of no overflow. See Figure 4 and Table 1 for overflow rates and other information. The dots on the lower curve show Hawaiian rainfall as 12-month running index means (Meisner 1976, figure 22). (×) and (+) symbols indicate early lake levels (see text).

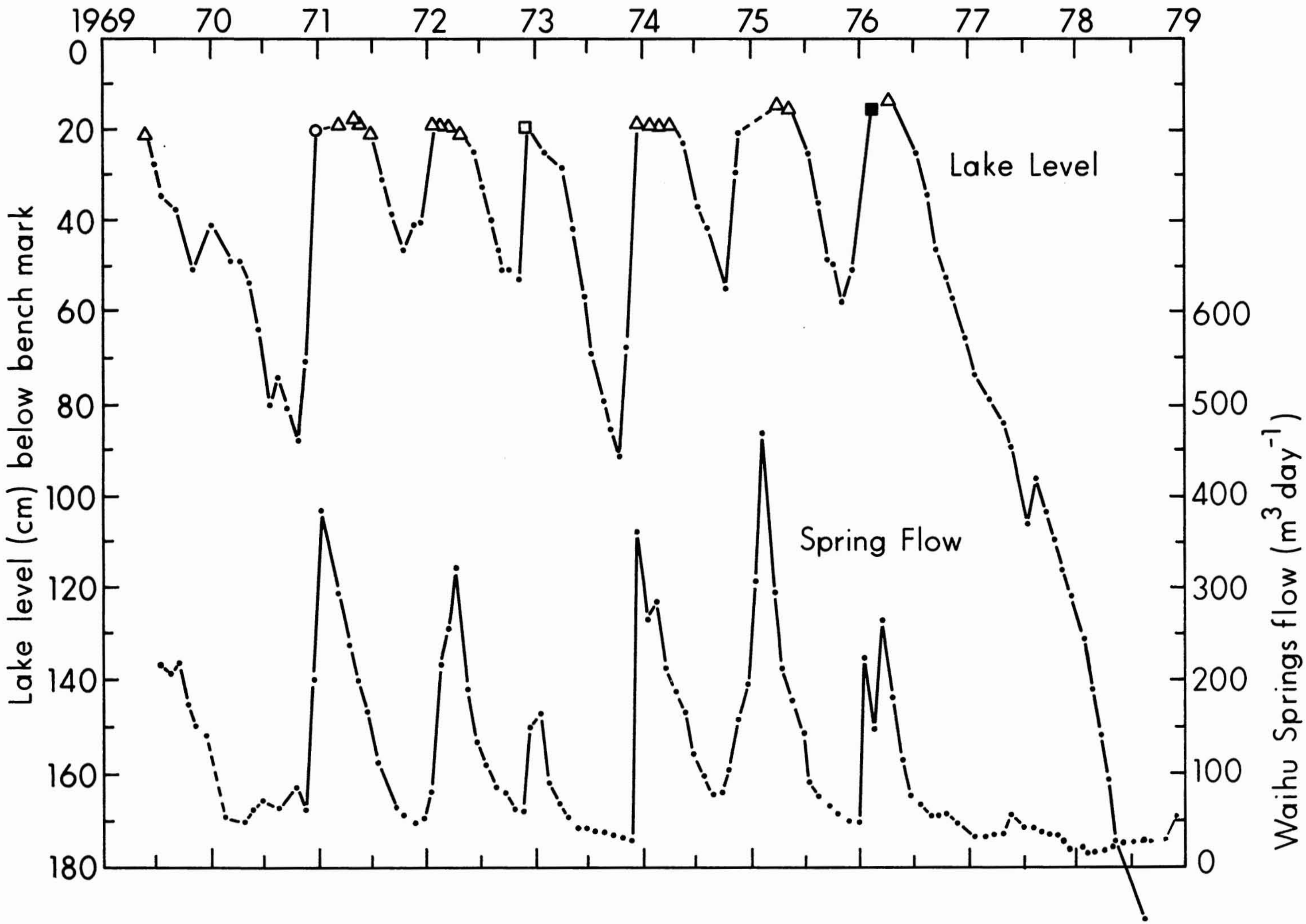

FIGURE 4. Lake Waiau level and Waihu Springs flow, 1969 to 1978. Upper curve shows differences in lake level, and lower curve gives average monthly spring flow. See Table 1 for comparative lake overflow and spring flow.

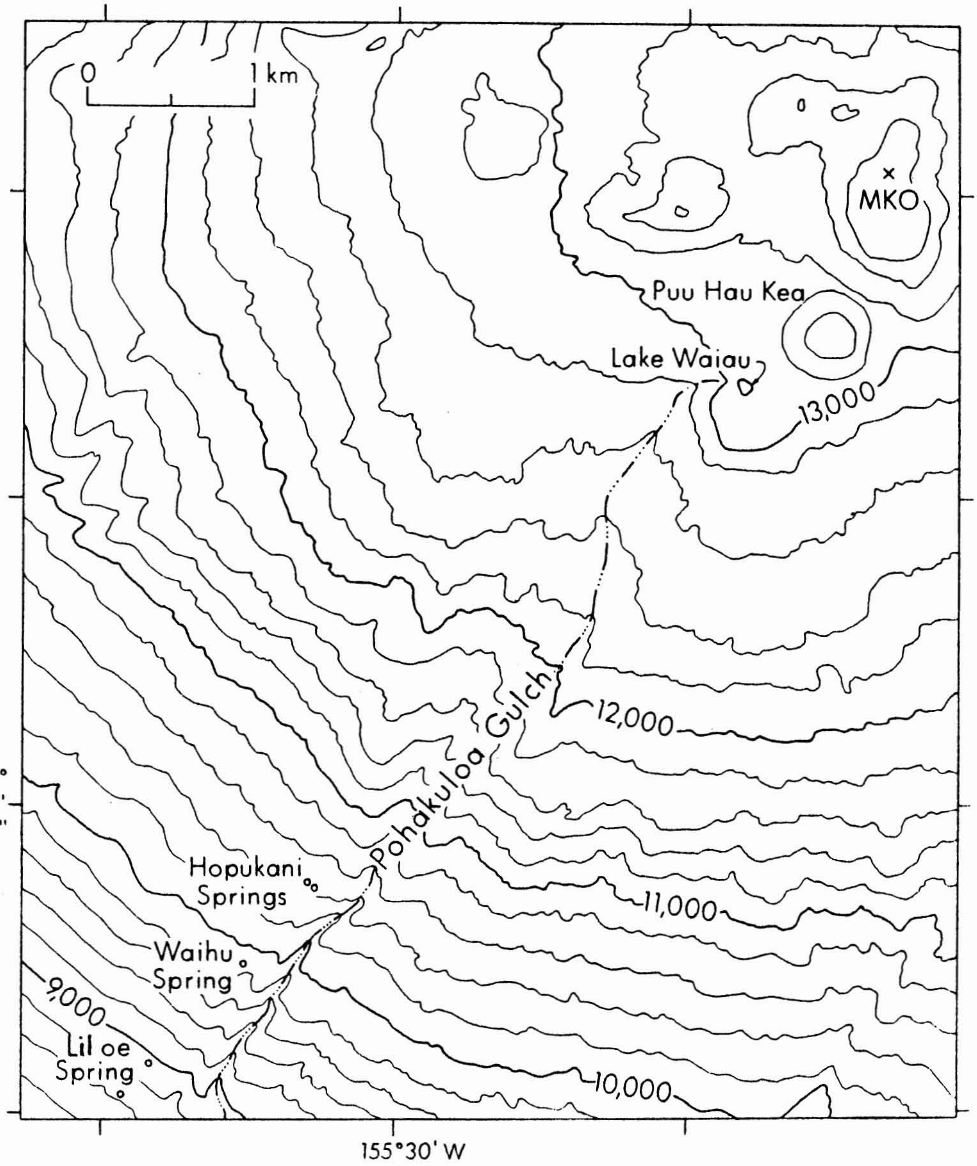

FIGURE 5. Reproduction from USGS topographic chart, Mauna Kea quadrangle, Hawaii, revealing relative locations and altitudes of Mauna Kea Observatory, Lake Waiau, Pohakuloa Gulch, and the springs. Altitudes in feet.

and about 4 to 6 km SSW of and from ~800 to 1200 m below LW. Figure 5 shows the location of these springs; they are hereafter referred to as the Waihu Spring (USGS springs #112, State of Hawaii 1970), or simply the springs. A system of interconnecting pipes carries the spring water down to the Pohakuloa Camp, where it is metered and stored for camp use. The quantities represent average total monthly flow of the several springs combined (Figure 4). During periods of high runoff, there is occasionally some water loss due to overflow at the small retaining structures on the mountain (T.

TABLE 2

TRITIUM CONCENTRATIONS IN PUU WAIAU GROUND AND LAKE SURFACE WATERS, AND IN WAIHU SPRING WATER

DATE	TRITIUM UNITS (0.0072 DPM/ml) GROUND	LAKE	SPRING	MONTHS SINCE LAKE FELL BELOW OVERFLOW STAGE
4 Oct 1969		60.1 ± 7.7		4
10 Nov 1969	43.3 ± 7.3			5
29 Jun 1973		34.8 ± 3.5	34.3 ± 3.1	6
1 Aug 1973		33.0 ± 3.1	45.8 ± 1.9	7
5 Sep 1973		39.2 ± 3.6	46.9 ± 1.9	8
5 Mar 1974		25.0 ± 1.0	30.1 ± 1.3	0
2 Apr 1974		26.6 ± 1.2	35.7 ± 1.5	0
30 Apr 1974		26.9 ± 1.1	37.1 ± 1.6	0
10 Jun 1974		25.9 ± 1.1	27.3 ± 1.1	1
Averages		30.2 ± 2.1	36.7 ± 1.8	
31 May 1977	12.7 ± 1.7	21.2 ± 2.3		12
22 Jul 1977	13.8 ± 1.9	20.9 ± 2.4		14
18 Aug 1977	13.3 ± 2.0	22.1 ± 3.0		15
20 Sep 1977	12.4 ± 1.4	20.3 ± 2.2	23.2 ± 3.1	16
19 Oct 1977	14.1 ± 1.9*	22.4 ± 3.1	21.6 ± 3.0	17
15 Nov 1977	12.9 ± 1.4*	21.6 ± 2.2	27.3 ± 3.2	18
13 Dec 1977	14.5 ± 2.0	21.5 ± 2.5	22.2 ± 2.8	19
18 Jan 1978	{15.3 ± 3.2 14.9 ± 3.0	26.5 ± 4.4	23.4 ± 3.2	20
21 Feb 1978	{13.1 ± 1.5 15.1 ± 1.7	22.1 ± 2.3	21.6 ± 2.4	21
21 Mar 1978	13.0 ± 1.7	23.0 ± 2.9	20.3 ± 2.4	22
Averages (Sep 1977 to Mar 1978)	13.9 ± 2.0	22.5 ± 2.8	22.8 ± 2.9	

*Samples taken only 1.5 m from the lake. Other groundwater samples taken ~10 m from the lake, at or near location no. 1 (Figure 2), by digging to the water level. Dual surface and 2-m-depth groundwater samples, taken on 18 Jan. and 21 Feb. 1978, reveal that the low-tritium water is not a surficial layer.

Nagata, personal communication; see photographs of springs, State of Hawaii 1970:139). This loss, which I understand is relatively small and of short duration, need not concern us here.

The tritium concentrations in the surface waters of the lake and groundwaters, and in the spring waters (Table 2), were determined by R. L. Michel, Department of Chemistry, University of California at San Diego, La Jolla; by Theo H. Hufen and W. A. McConachie, Water Resources Research Center, University of Hawaii; and by Teledyne Isotopes, Inc., Westwood, New Jersey 07675. Samples for tritium analysis were also drawn from 2 m below the groundwater surface by means of a simple driven-pipe and manual pumping technique. All water samples were collected by me.

The Hawaiian islands rainfall trend index (Figure 3) is taken from a study by Meisner (1976:1–4). He "updated an excellent study conducted by Solot in 1950," but altered the focus of the study from the problem of improving rain forecasting, to use of the index to reveal precipitation trends. This index, presented as 12-month running index means, is derived from the rainfall records of 27 climatically representative rain gauges on Kauai, Oahu, and Hawaii, and is thought to indicate trends in Hawaiian island-wide rainfall (Meisner 1976, figure 22). The additional indices on Figure 3, for the period beyond the 1973 limit of Meisner's figure 22, were contributed by B. N. Meisner.

LAKE LEVEL AND REGIONAL RAINFALL TRENDS

Figure 3, upper curve, shows ~14 years of observations of lake level; each symbol represents one measurement. Note that the lake level during overflow ranged from about 24 to 14 cm below the bench mark, and tended to decrease with time. I think that this trend is due to a progressive blocking effect by the grass growing among the stones in the outflow channel. The high overflow levels observed during the spring months of 1975 and 1976 are due to ice-damming and strong-wind effects. The record indicates that during about 80 percent of the time, lake level was well below overflow sill depth.

Figure 3 shows an apparent relationship between lake level and rainfall index, such that extended periods of relatively high stage and/or overflow are associated with higher than average rainfall index, and low stage with lower rainfall index.

The lake altitude is about 3960 m, where it is exposed to the dry air far above the NE trade wind inversion (see inversion study by Riehl et al. 1951). The average altitude of the 27 representative rain gauges from which the mean rainfall index was derived is only about 210 m (altitude range 3 to 715 m), which is far below the top of the trade wind moist layer at about 2400 m. The lake probably receives much if not most of its water from precipitation falling from the deeper layers of moist air often associated with winter storms. The brief Mauna Kea Observatory (MKO) precipitation record is not, however, adequate to test this presumption.

The relationship between lake level and statewide rainfall index may be due to the pronounced effect of winter storms on Hawaiian rainfall (Meisner 1976, figures 20, 21). The largest effect occurs at the relatively dry leeward locations (Solot 1950; Stidd and Leopold 1951). Note that the general downward trend suggested by the rainfall index (lower curve, Figure 3) and pointed out by Meisner (1976:35) is also indicated by the progressively lower low-stage of the lake over the 14 years of record (upper curve, Figure 3). As an indication of the probable correlation of lake level with rainfall trends at earlier times, we note that the August 1935 and the September 1942 low-stage observations by Wentworth (Wentworth film collection, box 5, film 14,046, Volcano Observatory, Hawaii) and by Stearns and Macdonald (1946:245) were preceded by several dryer-than-average years in Hawaiian mean winter rainfall index (Meisner 1976, figure 20). On Figure 3 these early low lake levels are indicated by the (×) and the (+) marks at the lower left side.

In the following sections of the paper the effects of the prolonged dry period (July 1976 to December 1978) are utilized in several other ways. The drought period has, in fact, presented a rare opportunity to learn more about this unusual lake and about its role as a water source for the Waihu Springs.

DISCUSSION OF LAKE LEVEL AND SPRING FLOW MEASUREMENTS

Some observers have suggested that lake overflow waters, which enter Pohakuloa Gulch above the springs (Figure 5), may be, in part at least, a source of the spring water (Bryan 1939). According to Wentworth and Powers (1943:542), however, these springs are "fed by ground-water bodies perched on or confined by intrusive bodies, ash beds or modern or ancient soils."

The springs have never been known to go dry (Bryan 1939). It appears that the same can be said of the lake, although during the 1976–1978 dry period the level fell more than 2.0 m below the outfall sill depth, and the total lake area was reduced by >40 percent (see area in October 1978, Figure 6).

On Figure 4 the monthy average spring flow since 1969 is plotted below a graph of the lake-level observations for the same period. Lake-level differences are of course clearly, although indirectly, related to spring flow amounts, through their mutual dependence upon precipitation and/or snow-melt

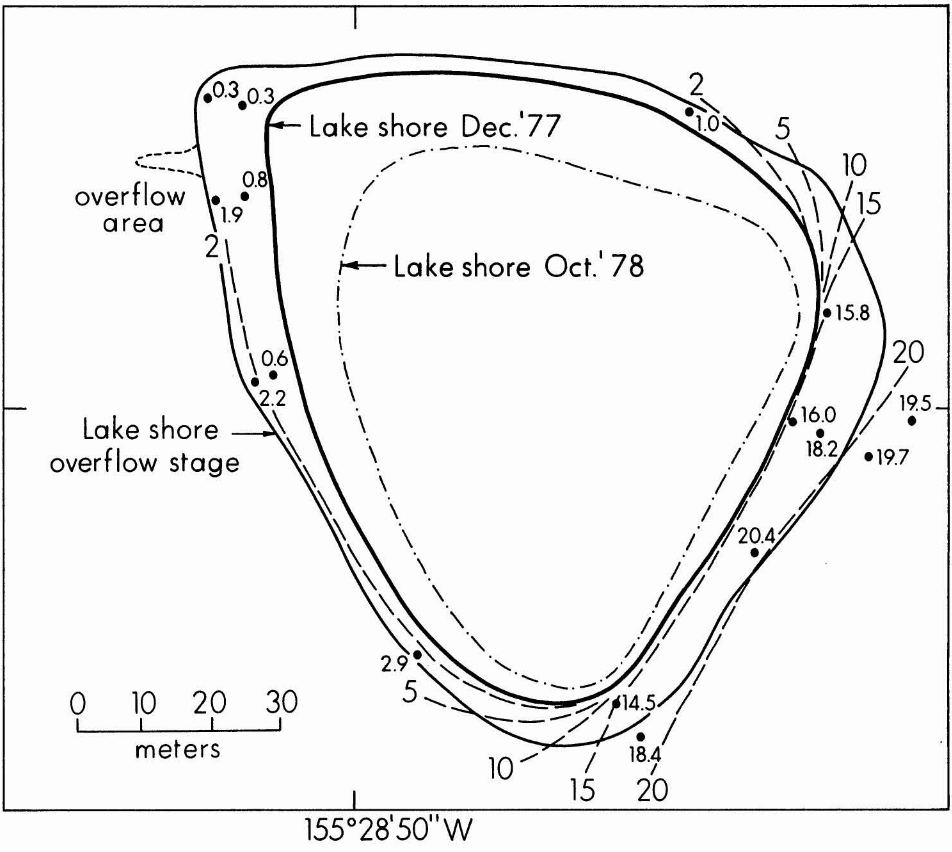

FIGURE 6. Perched groundwater levels in holes dug near lake in December 1977, about midway in dry period. Dots and adjacent digits show locations of holes and heights of water levels above lake levels (cm). The dashed lines are contours showing rough distributions of groundwater levels and suggesting a main water source eastward. Along the north shore, a steep lava-flow rampart marks an old ice-contact margin (Figure 1), where numerous boulders make digging impracticable. Lake area in October 1978, about 4070 m^2.

amounts at the upper levels on Mauna Kea. Whether there is a direct connection between spring flow and lake level and overflow is not immediately apparent; however, potentially useful conclusions can be drawn from a comparative preliminary study of the records of LW water level and overflow rates, and of Waihu Spring flow rates (Figure 4 and Table 1).

1. Obviously the spring flow cannot be dependent upon lake overflow as its only source, since spring flow was continuous, whereas the lake overflowed only about 20 percent of the time (Figure 4 and Table 1). When lake overflow did occur, the wide range in ratios of overflow to spring flow (Table 1) suggests little connection between them.

2. It is not correct to think that LW "rarely overflows" (Wentworth and Powers 1943, figure 2). Note on Figure 3 that during the long period from January 1967 to June 1968 the overflow appeared to be continuous. It is unfortunate that the spring flow record for this period of sustained high stage of the lake is missing or lost.

3. The average annual spring flow volume over the 8.6-year period, represented by the lower curve of Figure 4, is 41,500 m^3, or about 3.6 times the volume of the lake alone.

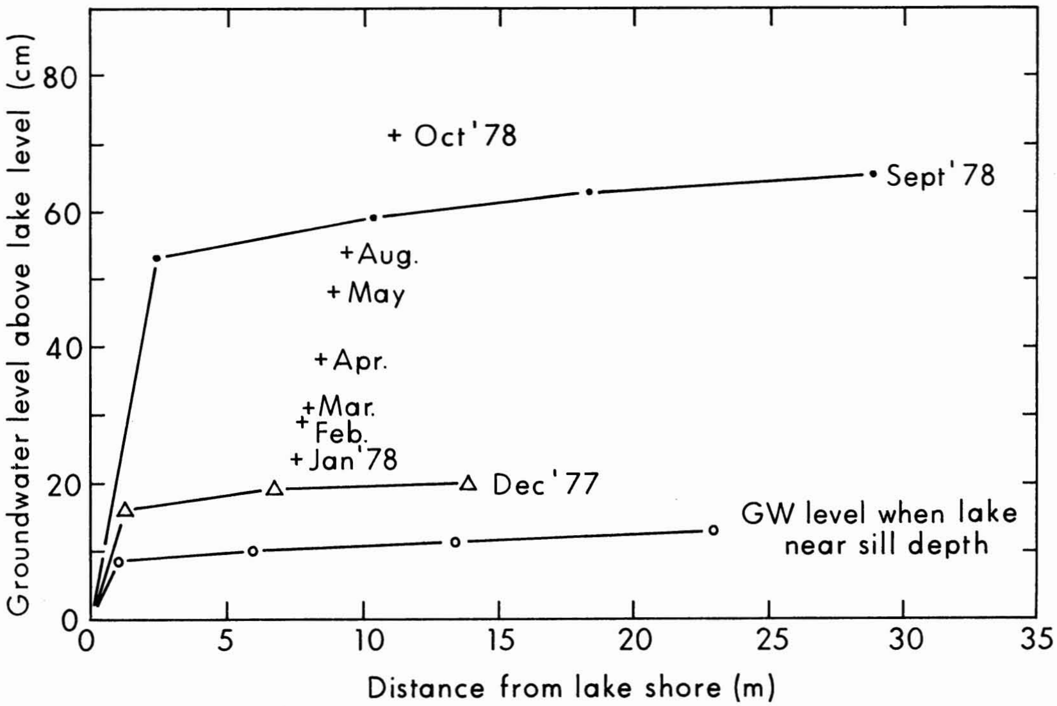

FIGURE 7. Elevation and slope of groundwater level relative to lake level at various times and distances along a line normal to the shore near location no. 1 (Figure 2). The line of single observations (+) represents measurements made at location no. 1, January to October 1978. The bottom curve is from Woodcock and Groves (1969, figure 9).

The LW volume at overflow stage (i.e., ~11,600 m^3), is derived from the depths and areas of Figure 2. (Stearns and Macdonald [1946: 245] estimated a lake volume of 13,200 m^3, but their estimate predated the availability of the more detailed soundings used here [Figure 2].) The lake volume, however, represents an uncertain fraction of the total water content of Waiau crater, as shown in conclusion 5 below.

4. During 1977, 36 percent (8.32 cm) of the total annual rain at MKO fell during 4 days, between the 6th and the 12th of August; most of it on one day (from NOAA climatological data, 1976, 1977, 1978). It is interesting that a 10-cm rise in lake level resulted from these summit area rains (Figure 4), but that there was no change in the slow but steady decrease in spring flow rate over the following days and weeks. This suggests a marked insensitivity of the springs to rains at the summit area.

5. The volume of water in the lake sediments and in the perched ground waters of the crater would add considerably to the volume of water in Waiau crater, as estimated from the lake depth and area alone. For instance, note that the top 3-m section of the >6-m-layer of sediment under the lake is ~50 percent water (Woodcock and Groves 1969, figure 6). Also, a groundwater layer of at least 2-m depth extends into the crater beyond and above the east shores at least 30 m (see Figures 6 and 7). Thus the volume of water in Waiau crater will much exceed that estimated simply from the area and depth of the visible lake at the overflow stage.

6. Seepage from LW might seem a likely source of at least part of the spring water. Note that during long dry periods (e.g., May to November 1973, and July 1976 to January 1979, Figure 4) the spring flow is low but tends to be relatively constant, suggesting a large seepage source such as the lake. How-

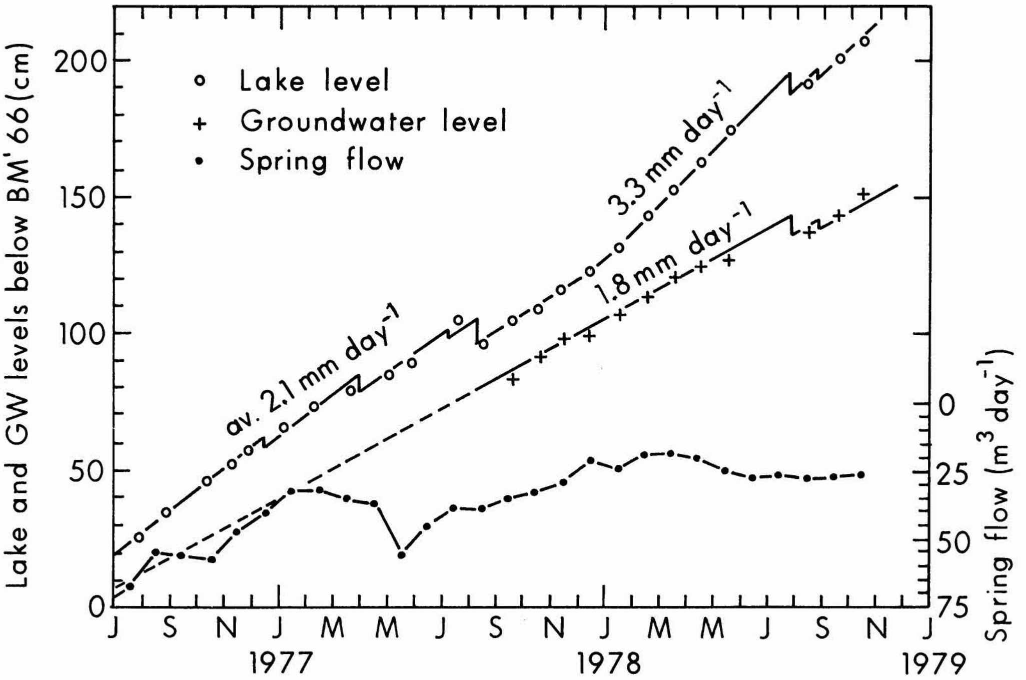

FIGURE 8. Reduction in levels of lake and ground waters and in spring flow rate during drought, July 1976 to November 1978. The point of origin of lake-level line marks beginning of dry period, and that of the groundwater is taken from observations when lake was much nearer overflow stage (Woodcock and Groves 1969, figure 9). March and April 1978 spring-flow values interpolated in part on days during repair of pipe system. See text.

ever, the high permeability of the ash and cinder of the MK summit area (Woodcock and Friedman 1979) makes the required 4 to 6 km of horizontal diversion of lake seepage water to the springs (Figure 5) seem doubtful.

The following hydrogen isotope study of MK waters indicates, nevertheless, a probable seepage connection between lake and springs.

TRITIUM CONCENTRATIONS OF LAKE, SPRING, AND GROUNDWATERS

Evidence that LW is the source of the spring water during dry periods of long duration lies in the comparative tritium concentrations of the two waters (see example of other uses of tritium in the investigation of Hawaiian waters by Hufen 1974). Note that during relatively short dry periods and during wet periods of lake overflow (Table 2, first 7 lines), the average differences in the tritium concentration of the lake and spring waters were greater than they were following the drought of 16 to 22 months duration (Table 2, last 7 lines). This result suggests that other spring-water sources diminished or dried up during the long drought, and that the lake finally became the only spring-water source.

The lake is the only known adequate and potentially constant source of water during the 2.5-year dry period. There *is* a deep layer of permafrost of unknown horizontal extent in the crater of the summit cone, but the tritium concentration of this permafrost is probably too low for its melt waters to be considered as the spring source (see Woodcock 1974, table 1). I think, therefore, that the tritium analyses are substantial evidence of the major role of seepage from LW in the spring flow during prolonged dry weather.

As seen in Table 2, the tritium concentration of the groundwater is lower than that of the spring water during the drought, while the tritium of the lake and spring waters is about the same. This suggests that direct seepage from the groundwater to the springs does not occur. The water flow (see groundwater lowering rate, Figure 8) is probably by slow seepage from the groundwater to the lake around the lake rim (e.g., Downing and Peterka 1978) and then by seepage from the base of the lake sediments to the springs. Thus a relatively impervious layer apparently is present beneath the groundwater, but is absent under the lake itself (also see Woodcock and Groves 1969:252–253). Otherwise, if direct seepage of groundwater and lake water supplies the springs, the tritium of the spring water should lie between that of the groundwater and lake-water values, the concentration depending upon the proportional contribution of each source. This result is not observed.

Ugolini (1974) has suggested a hydrothermal origin of much of the fines in Waiau cone, resulting from lava contact with melt water from an ice cap during eruption. A deep layer of fine sediment and organic debris is known to occur immediately under the lake (Woodcock and Groves 1969; Woodcock, Rubin, and Duce 1966); this layer would, of course, overlie the eruptive fines. If fines alone controlled seepage, one would expect a reverse of the apparent observed seepage situation during droughts, with seepage more rapid from groundwater to springs than from lake to springs.

An explanation for this anomalous seepage is that relict permafrost may underlie the groundwaters, but that downward heat flow from the lake (Adams et al. 1976) has melted the permafrost under the lake, allowing seepage there. This condition is in part observed under lakes in permafrost regions at high latitudes (e.g., Johnson and Brown 1964), and several factors make it seem likely at LW.

1. A deep layer of permafrost exists in a nearby crater (Woodcock 1974). (Clearly we were incorrect in our earlier opinion that the MK summit-area climate was probably too warm for permafrost [Woodcock and Groves 1969:452].)

2. Negative temperature gradients are found in the sediments under LW (Woodcock and Groves 1969).

3. Negative temperature gradients are found in two other nearby locations (Woodcock and Friedman 1979).

Thus tritium concentrations of lake, ground, and spring waters indicate that lake seepage is the source of spring flow during droughts, and that the groundwater may be underlain by permafrost.

Other aspects of the observations of groundwater and lake levels and of spring flow are also of interest.

PERCHED GROUNDWATERS OF WAIAU CRATER

Flow of groundwater into LW probably occurs by seepage from the lake sediments near the shore, especially along ~ 100 m of the east shore, where the main hydraulic gradient between the two waters occurs (Figure 6). The difference in the height of perched groundwater level relative to lake level may be due to differences in the size of areas drained, since the higher points in the groundwater level lie along that part of the east shore closest to the larger drainage area of the crater (Figures 6 and 7). Groundwater level differences may be due to other factors, such as differences in the permeability of the near-shore sediments, or in the elevations of groundwater sources and sinks within the crater, relative to the deep Pohakuloa Gulch on the NW side (Figures 1 and 5).

It is noteworthy that, over the drought period September 1977 to March 1978, seepage from groundwater to lake produced no apparent decrease in the lake's tritium, despite the low value in the groundwater (Table 2). A balance may have existed between the effect of the inflowing groundwater in reducing lake tritium concentration and the effect of evaporation from the lake in increasing the concentration. The enrichment of the heavy isotopes due to fractionation accompanying evaporation in water exposed to the atmosphere has been shown in a study by Gat (1971).

Lake and groundwater level differences were smaller during the higher lake stage of the early drought months, up to December 1977, and then became much greater as the

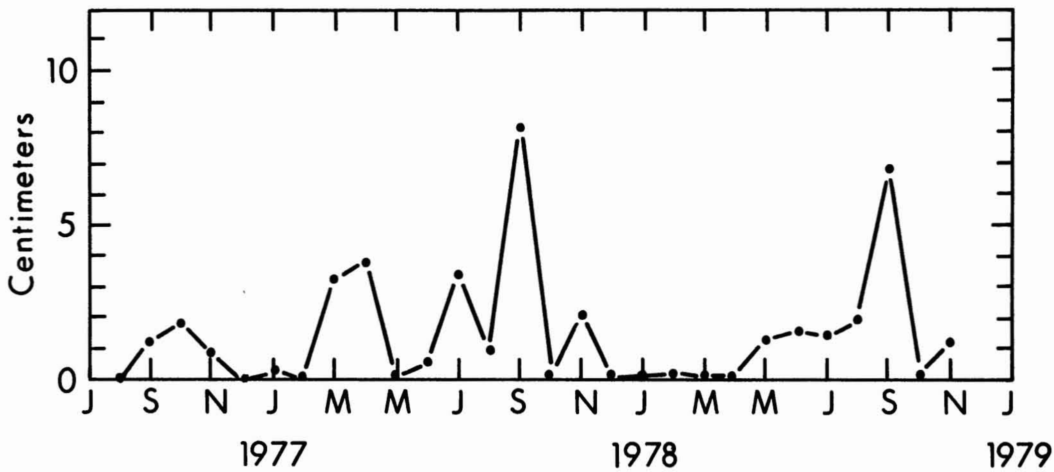

FIGURE 9. Precipitation at MKO during drought (from NOAA, Environmental Data Service, 1976, 1977, 1978).

dry weather continued (Figure 7). Figure 8 shows a combined and more detailed picture of the general reduction of lake and groundwater levels, and of spring flow. In this figure the observed changes in lake level are shown more clearly than in Figures 3 and 4, and are compared to changes in groundwater levels measured largely during the latter half of the dry period (Figure 7).

It appears from the slope of the lines in Figure 8 that the rate of lowering of the lake and groundwater levels was about constant between 1.8 and 2.1 mm day^{-1} until early in 1978. (Note adjustment of lines for local rain amounts [Figure 9] represented by the short vertical displacements, such as that in August 1978.) In early 1978 the lake lowering rate increased to 3.3 mm day^{-1}, but the rate of reduction of groundwater level remained about the same at 1.8 mm day^{-1}. As a result, the average level of the groundwater above the lake increased markedly in 1978 (Figure 7), thus building up the hydraulic gradient between them.

It seemed reasonable to expect that this increase in hydraulic gradient would increase the flow into the lake from the groundwater (e.g., see Downing and Peterka 1978). If so, a gradual increase in the rate of lowering of groundwater level would be expected. However, this effect did not occur over a period of many months (Figure 8). Thus I seem to have found an anomalous condition, with a nearly constant but different rate of lowering of lake and groundwater levels, in the presence of a steadily increasing hydraulic gradient between them. I tentatively interpret this to mean that as the hydraulic pressure increased, the internal resistance to flow between groundwater and lake also increased, in some unknown way.

The cause of the increased rate of lake level lowering in early 1978, accompanying a time of decrease in lake size, is not known. It was suggested that increased temperatures in the shallow lake might increase evaporation and the rate of lake-level change. However, the lake temperature range, measured monthly from November 1977 to November 1978, was $\sim 3°$ to 12°C, which is the usual temperature range in LW at normal stage (see figure 3, Woodcock and Groves 1969).

At first I thought that the change in lake lowering rate might be followed by a change in the rate of spring flow, but there is no clear indication of this. The spring flow generally decreased during all of the drought period (see bottom curves, Figures 4 and 8), with some relatively small increases in flow that were probably related in part to rains at lower altitudes near the springs, as indicated by the Hale Pohaku rainfall (see NOAA climatological data, 1976, 1977, 1978).

It is interesting that the MK summit-area rainfall seems to be simply additive to LW and groundwater levels. Note in Figure 8 that the short vertical lines correspond in length to amounts, or cumulative amounts, of rain observed at MKO (Figure 9). It seems that there is little or no surface and subsurface inflow into the Waiau lake and groundwaters from the surrounding catchment area of the crater, which is estimated to be about 20 times the lake area at overflow stage. I tentatively interpret these observations to mean that rainwaters percolate into the porous ash and cinder, with little or no immediate lateral and subsurface runoff (see MK drainage discussion, Gregory and Wentworth 1937), and that they are only retained in the lake and groundwaters by the relatively impermeable materials directly under these areas. Thus it appears that the lake and groundwaters are like a rain gauge, in the sense that, in the short term, they receive from the rain only those waters appropriate to their respective areas. Slow seepage from the groundwater to the lake then produces the gradual lowering of its level, as revealed in Figure 8.

From what is known at present, this unexpected initial finding probably indicates that the combined lake and groundwater reservoir areas are about equal to the estimated surface water catchment area of the crater, due to the presence within the crater of extensive layers of fines and permafrost, or both. Thus a large area of groundwater around LW is indicated—water largely shielded from loss by evaporation due to the ground layers (e.g., see White 1932), and apparently from loss by bottom seepage as well, due to permafrost.

The groundwater around LW probably plays an important role in the survival of the lake in the arid climate of the MK summit. Eventual melting of permafrost blocking direct seepage from the groundwater to the springs may so increase the rate of water loss from Waiau crater as to threaten the continued existence of LW as a perennial body of water.

Preliminary observations in November 1978 revealed a different response to snow melt waters in Waiau crater than that revealed earlier to rain waters. Further work is needed to clarify the nature of the response of lake and groundwaters to rainfall and snowfall.

CONCLUSIONS, COMMENTS, AND RECOMMENDATIONS

Lake water level appears to be related to trends in state-wide rainfall index, including a trend toward an increasingly low low-water stage that parallels the increasing severity of drought over the 14-year period of study. This result probably reflects the important role of winter storms in alpine precipitation on MK, as well as in state-wide rainfall.

Study of the comparative tritium concentrations of lake, ground, and spring waters supports the idea that lake seepage supplies spring water during droughts, and that direct seepage from the groundwater to the springs is blocked by a layer of relict ice.

The effect of rains in raising lake and groundwater levels by an amount equal to the amount of rain suggests that the combined areas of the lake and groundwater reservoirs about equal the Waiau crater horizontal surface area.

The strongly asymmetrical distribution of the Waiau cone groundwater level, following the 18-month dry period, suggests that the main groundwater source is eastward.

I recommend the establishment of water level and overflow gauges at Lake Waiau. Records from these gauges may add to our understanding of the significance of lake level and overflow, relative to state-wide droughts and long-term precipitation trends.

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