MACLURE GLACIER, CALIFORNIA 1/

A Contribution to the International Hydrological Decade

By

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Introduction

This report on a study of Maclure Glacier in California is appropriate for the theme of the 1974 Western Snow Conference "Man and Arctic and Alpine Snow Hydrology." One does not ordinarily associate California with matters arctic and alpine. Yet California has more than 100 small living glaciers high in the Sierra Nevada, the Trinity Alps, and on Mount Shasta. The estimated total glacier area in California of 20 km^2 (square kilometers) is the smallest for any Pacific Coast State or Province and is infinitesimal compared to the estimated 73,000 km^2 area of glaciers in Alaska (Tangborn, oral commun., Dec. 5, 1973). Maclure Glacier with 0.17 km^2 would be lost next to the Bering Glacier near Cordova, the largest glacier in North America with an area of 5,800 km^2 and a length of 200 km (kilometers).

The glacial processes at work on Maclure are similar to those governing the Bering and other large glaciers. Thus Maclure Glacier is a good model for its big brothers. Small glaciers permit quantitative measurement and analysis of greater precision than is possible for large ice bodies. The Maclure study by the Geological Survey from 1967 through 1972 was part of the United States contribution to the International Hydrological Decade.

International Hydrological Decade.--IHD 1965 to 1974 was designed to promote international cooperation in research and studies and the training of specialists and technicians in scientific hydrology. An important IHD project is to define ice and water balances and changes with time at selected glacier basins in many parts of the world. Three chains of glacier basin stations are being operated, one generally north-south along the western mountains of the Americas from Arctic Alaska to the Antarctic, a second covering a global zone centered about 45^0 North latitude, and the third a more northerly zone at about 66° North latitude. The north-south IHD glacier basin chain in North America includes Maclure Glacier in California, South Cascade Glacier in Washington, Berendon, Place and Sentinel Glaciers in Canada and Gulkana, McCall and Wolverine Glaciers in Alaska (UNESCO/ LASH, 1970, app. 1).

Description of Maclure Glacier.--Maclure Glacier is located near the crest of the Sierra Nevada in Yosemite National Park in east-central California (fig. 1). The glacier is in a north-facing cirque on Mount Maclure just west of the somewhat larger and better known Lyell Glacier. Effluent streams from both glaciers constitute the headwaters of the Tuolumne River which is the primary water supply for the city of San Francisco and a major source of irrigation water for part of the San Joaquin Valley. Maclure Glacier is 0.4 km long and has an area of 0.17 km^2 (fig. 2). Its altitude ranges from 3,600 to 3,800 m (meters). The Maclure Creek drainage basin has an area of 0.97 km^2 above the stream gaging station and has several other small ice bodies in addition to the main glacier.

The north-facing location and the altitude of Maclure Glacier are characteristic of glaciers sprinkled along the crest of the Sierra Nevada from latitude 36°45° to 38°10° N. Practically all these glaciers face north or east and are situated in glacial cirques that were eroded by much larger Pleistocene glaciers. Map reconnaissance indicates that the glaciers are in pockets where windblown snow can accumulate. The glaciers are found in an altitude zone from 3,000 to 4,000 m and are generally at higher altitudes to the south. The altitude of the glaciers is related to the altitude of protecting ridges and peaks.

Previous Investigations.--Maclure Glacier was the subject of the first quantitative glacier study on the continent. In October 1871, John Muir described the ice bodies on Mount Maclure, Mount Lyell, and neighboring peaks as living glaciers (Russell, 1885, p.324).

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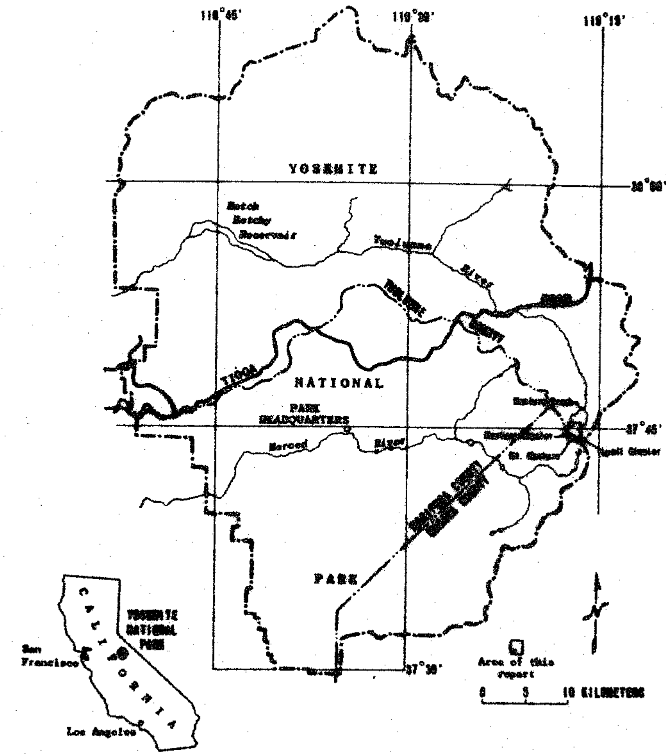

FIGURE 1.—Index map of Maclure Glacier in Yosemite National Park

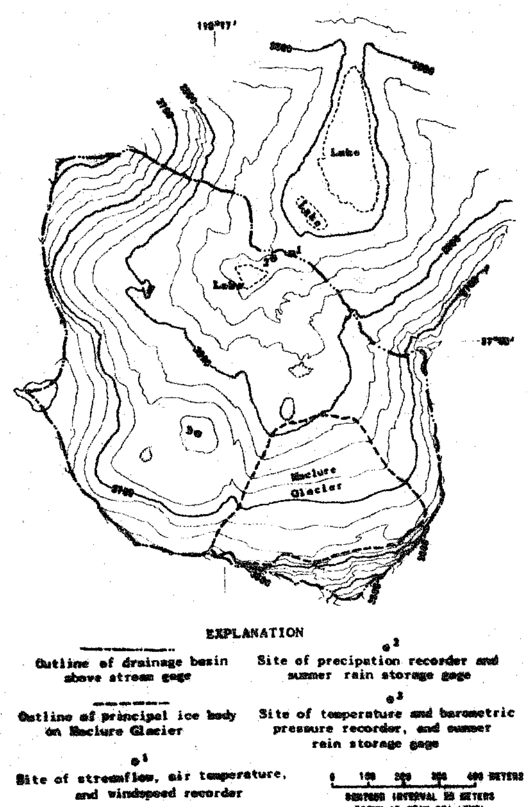

FIGURE 2.—Instrumentation in Maclure Creek Basin, Yosemite National Park

In August 1872, Muir set four stakes in a line from the east side of Maclure Glacier to a point near the middle. In October the middle stakes had been carried 47 inches (119 centimeters) down the glacier in a 46-day period. The other stakes had been moved lesser distances.

Israel C. Russell observed Maclure and other glaciers in 1882 and 1883. Russell commented that based on previous accounts of the extent of the snowfields, it seemed evident that melting had counterbalanced annual additions during the past few years (Russell, 1885, p. 323). A sketch in the Russell report shows that Maclure Glacier was twice its present length with the terminus at the upstream shore of the larger lake (fig. 2).

Francois E. Matthes began extensive studies of Yosemite National Park in 1913 that resulted in a detailed analysis of the geologic, geomorphologic and glacial history in the ,park A map of ancient glaciers of the Yosemite region (Matthes, 1930, pl. 39) outlines areas of about 1,500 km^2 of glacier ice at the maximum Pleistocene stage compared to 1 km2 at present. The Pleistocene Maclure Glacier flowed into the massive Tuolumne Ice Field that moved northward and westward 150 km to a terminus below the Hetch Hetchy valley.

Matthes concluded that all Sierra Nevada ice melted following the end of the last or Wisconsin stage of Pleistocene glaciation (Matthes, 1947, p. 210-214). World temperatures rose to a climatic optimum about 4,000 years ago. Temperatures then dropped, first slowly, then more rapidly during the last millennium B.C. Alpine glaciers grew larger and about 1600 A.D. descended into valleys and overwhelmed pastureland and villages. Other advances followed in the seventeenth, eighteenth, and nineteenth centuries. A general recession began after the middle of the nineteenth century. Maclure and other Sierra Nevada glaciers are the product of the "little ice age" of historic time rather than remnants of Pleistocene glaciers.

The National Park Service began annual early autumn observations in the 1930's of Lyell and Maclure Glaciers and less frequently of other glaciers in the park. The advance or retreat of terminal ice fronts was measured. A cross section was surveyed annually across Lyell Glacier between established reference points and pictures were taken from photo reference points. Review of several annual reports (National Park Service, 1931-59) indicates that Lyell and Maclure Glaciers receded during the 1930's.

Methods

The methods for the Maclure Glacier study are those adopted for the worldwide IHD glacial studies. The methods are described in IHD technical papers in hydrology (UNESCO/IASH, 1970) and in Meier and others (1971). The primary objective is to determine the annual ice and snow balance on the glacier. Runoff can be measured only for a larger area designated as Maclure Creek basin. A separate annual snow and ice balance and an annual water balance are estimated for Maclure Creek basin. All results are computed in volumes in cubic meters of equivalent water and are expressed in average vertical depths in meters over Maclure Glacier or the Maclure Creek basin.

The original IHD study proposal specified measurement of annual ice, water, and heat balances at selected glacier basins. Most countries have found that heat balance or energy exchange results are difficult to obtain and have temporarily abandoned the attempt.

Glacier mass balance studies require measurement of accumulation and ablation. Accumulation means all processes by which solid ice is added to a glacier. Accumulation processes include precipitation as snow, water, or ice, transportation of snow or ice by wind or avalanches, refreezing of liquid water and condensation of ice from vapor. Ablation means all processes by which snow and ice are lost from a glacier including melting, removal by wind or avalanches, the physical loss of ice at the glacier terminus and evaporation. Studies by La Chapelle on Blue and by Meier on South Cascade Glaciers indicated that condensation and evaporation quantities are approximately equal and that the difference is relatively small and can be omitted from balance studies.

Annual net balances were computed by glacial years for both Maclure Glacier and the Maclure Creek drainage basin including the glacier. A glacial year ends at the date of minimum glacial mass at the end of summer snow and ice melt and the beginning of accumulation of the next season's snow. The Maclure glacial year very nearly coincides with the hydrologic year of October 1 through September 30. Mean air temperature at Maclure drops well below freezing in late September and streamflow diminishes to a trickle. The first autumn storm in September or October starts a new snowpack. No attempt was made to obtain winter streamflow records, but scattered observations indicated that there is no runoff during the period from November through mid-May.

The net balance at the end of a glacial year equals the gain as the unmelted part of the year's snowpack minus any loss of ice and firn from previous years. The unmelted snow, or firn, at the end of the year is gradually metamorphosed into glacial ice. Although glacial balance computations may be made on a cumulative daily basis, this report deals only with annual totals.

Instrumentation.--The fixed instrumentation for the Maclure study included equip-0 ment at the three sites shown in figure 2. At site 1 streamflow, air temperature, and wind-speed were recorded on a negator-spring-driven A-35 recorder at the lower end of the 0.97 km^2 Maclure Creek basin. This recorder was housed in a timber shelter above a 90° sharp-crested weir in a timber dam across the stream channel. The air temperature probe and anemometer were located on a mast 5 m above ground.

At site 2 about 50 m west from site 1 accumulated precipitation was recorded on another A-36 instrument. The 20.3-cm(8-inch) diameter rain-gage orifice was positioned 4 m above ground. A standard rain gage on a 4-m steel tower was used to measure summer precip-itation. The precipitation gages were equipped with modified Alter windshields. At site 3, on an exposed knob at an altitude of 3,680 m, air temperature and barometric pressure were recorded. The air-temperature probe was located 4m above ground on a steel tower that supported another standard rain gage to measure summer precipitation.

A detailed map by the U.S. Geological Survey on a 1:2,500 scale, with 5-m contour intervals from aerial photographs served as the base for all subsequent glacier surveys.

Field and Office Procedures.--After 1966 instrumentation, field work was performed each year by a 2- or 3-person crew during 3 several-day periods in late May, mid-July, and late September or early October. Recording instruments were serviced at each visit and non-recording precipitation gages were activated for the summer period. Special work included the following:

May--1. Probe snow depth to last year's firn or to rock at several hundred points over glacier and basin, and dig 1 or 2 pits for density profiles. Probe points were located with a Brunton compass survey.

2. Drill holes and set ablation stakes, recording depth set in snow and ice.

3. Photograph glacier and basin for photomontages from several vantage points to define snow coverage.

July--1. Measure depth change at ablation stakes. Drill new holes and reset stakes, if necessary.

2. Probe snow depth at ablation stakes. Drill new holes and reset stakes, if necessary.

3. Make several current-meter measurements of streamflow at different times during the diurnal cycle.

September--1. Measure depth change at ablation stakes.

2. Measure the depth and density of any snow remaining at stakes.

3. Measure the advance or retreat of glacier terminus.

4. Measure streamflow.

5. Repeat May photographs.

In the office, field data on snow depths and density in May were reduced to water equivalents in meters. The May water equivalent is the late-winter balance because all precipitation since the previous September had accumulated as snow. Field data on changes in snow and ice depths determined the September net balance gain or loss at each point of measurement. The net balance equals any residual snow in September at the end of the melt season minus the ice and firn ablation during May through September. A positive net balance indicates a gain in glacier mass at that point for the year and a negative net balance indicates a loss.

Annual glacier mass balance computations were based on maps of late-winter balance and September net balance. Contours of equal water equivalent were drawn by meters or half-meters. Photographs and field notes were studied to delineate bare rock areas in May and September. Areas of equal water equivalent on each map were planimetered for each 25-m altitude zone. Separate computations were made for the glacier and nonglacier areas. Water volumes, in cubic meters, were computed by multiplying the planimetered areas by contoured water equivalents and summing volumes for each 25-m altitude zone. Average depths, in meters of water, of winter balance were computed for each altitude zone.

Finally annual totals of winter balance and net balance were computed for the glacier and for the drainage basin by adding zonal volume figures. Average depths equal total volumes divided by the glacier or basin area. Accumulation (winter balance) minus net balance equals total ablation. A summary of ice and water data follows.

Table 1.--Summary of ice and water data

Symbol	Item	Unit	Year					
			1967	1968	1969	1970	1971	1972
			Maclure Glacier (0.17 km^2 area)					
b_w	Winter balance	m	3.66	1.23	2.51	1.53	1.50	1.38
$a_t(s)$	Ablation of snow	m	2.18	1.16	1.67	.80	1.39	1.26
$a_t(i)$	Ablation of ice and firn	m	.07	.83	.18	.47	.59	.89
b_n	Net balance	m	1.21	-.76	.66	.26	-.48	-.77
AAR	Accumulation area ratio	---	.86	.18	.73	.45	.43	.33
ELA	Equilibrium line altitude	m	3,640	3,740	3,670	3,710	3,700	3,720
AL	Advance (+) or retreat (-)	m	+5	-4	+7	-3	-5	-2
			Maclure Creek basin (0.97 km^2 area)					
b_w	Winter balance	m	1.98	.59	1.65	1.01	.93	.73
$a_t(s)$	Ablation of snow	m	1.58	.58	1.28	.82	.91	.71
$a_t(i)$	Ablation of ice and firn	m	.01	.28	.03	.19	.16	.21
b_n	Net balance	m	.39	-.27	.34	0	-.14	-.19
pr	Precipitation as rain	m	.14	.02	.05	.02	.03	.10
pt	Recorded precipitation at site 2	m	2.03	.61	1.70	1.16	1.36	.96
r	Measured runoff	m	1.51	.89	1.28	1.08	1.01	1.00
AAR	Accumulation area ratio	---	.93	.03	.38	.20	.08	.09
r^*	Calculated runoff ($a_t(s) + a_t(i) +$ pr)	m	1.73	.88	1.36	1.03	1.10	1.02
$r^* - r$	Error in runoff	m	.22	-.01	.08	-.05	.09	-.02

The preceding table includes an annual equilibrium line altitude for the glacier that is based on the location of the zero contour on the annual net balance map. The accumulation area ratios for the glacier and basin equal the sum of all residual snow areas on the September map divided by the total area. Runoff data expressed in meters of water over the basin were obtained from operation of the recording stream gage and standard streamflow record computation. Based on current-meter measurements, the rating curve was slightly larger than a theoretical rating for a 90° weir because of leakage under the small dam.

Discussion of Results

For both the glacier and basin, the snow residual (winter balance minus ablation of snow) minus the ablation of ice and firn equals the net balance. The annual net balances for Maclure Glacier indicate gains during 3 years and losses in 3 years (fig. 3). The net balance suggests a slight increase for the 6-year study period. Individual values are smaller for the Maclure Creek basin but results are similar to those for the glacier. For the Maclure Creek basin, snow ablation plus ice and firn ablation, plus summer precipitation as rain approximately equals runoff during 1967 to 1972. This comparison disregards unmeasured condensation gains and evaporation losses.

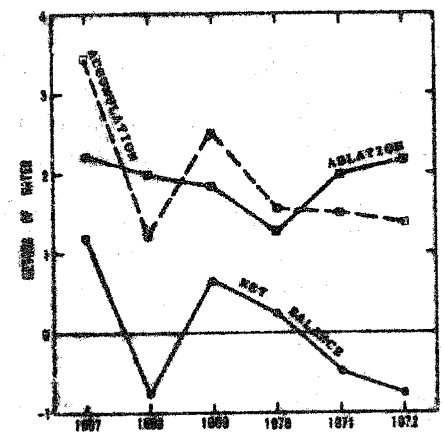

FIGURE 3.--Annual accumulation, ablation, and net balance on Maclure Glacier during 1967-72.

Any conclusions from the Maclure data must consider the accuracy of data. Standard errors have not been computed but approximations would be about plus or minus 20 percent for winter balance figures and 30 percent for snow and ice ablation results. Measured runoff should be within 5 percent. The standard error of the difference between calculated runoff and measured runoff (table 1) was 0.10 m. The ablation data for the nonglacier area are less accurate when a dry year follows a wet year and the nonglacier firn area is reduced as much as half. Approximations of water loss are made from the area reduction and estimated depth loss.

An unknown in the water balance analysis is the amount of melting of any ice under the extensive moraine area below Maclure Glacier. The Park Service observed exposed ice under the terminal moraines of Conness and Dana Glaciers at the end of several low years. The environment of these glaciers is similar to that at Maclure. However, the Maclure Creek basin water balance indicates that the contribution from ice melt under the Maclure moraine is small.

The precipitation recorded at site 2 (fig. 2) is listed in table 1 for comparison but is not used in computations. The late-winter balance based on the integration of many snow depths over the basin is a better measure of true total precipitation than the catch at a single gage. The precipitation as rain is the average catch at the two summer rain gages operated from May through September. Because the precipitation recorder at site 2 stopped part of each winter, daily distribution of the total precipitation was estimated on basis of daily precipitation records at Yosemite Park Headquarters 26 km to the west. The synthetic daily record at the glacier was used in daily glacial balance studies.

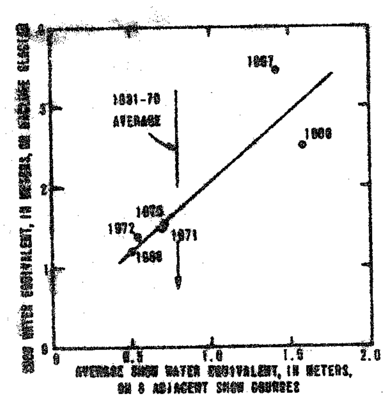

FIGURE 4.--Comparison of annual snow water equivalent on Maclure Glacier to average on 8 adjacent snow courses

Comparison to Snow Course Records.--Records for nearby snow courses were used to relate the 6-year record for Maclure Glacier to longer climatological records. Figure 4 is a plot of winter balance in meters on the glacier from 1967 through 1972 against the average water equivalent at eight high-altitude snow courses. The eight courses are situated in all directions from the glacier at distances from 8 to 18 km and altitudes from 2,560 to 3,170 m on the headwater areas of the San Joaquin, Tuolumne, and Mono Lake basins. April 1 survey data were used for the snow courses except for 1967 when May 1 surveys were made because of unusually heavy April snowfall.

A 1931-70 average of 0.79 m was computed for the eight-snow course combination using individual course averages published by the California Department of Water Resources (1971). From figure 4, the 1931-70 average annual snow water on Maclure Glacier was estimated as 1.7 m, compared to the 1.94 m average measured in 1967-72. Similarly the 1931-70 average for. Maclure Creek basin was estimated at 1.0 m, compared to 1.15 m in 1967-72. The 1.0 m long-term estimate for the basin agrees with the estimated mean annual precipitation in this area (Rantz, 1969). The larger snow accumulation on the glacier results from windblown snow and avalanches. The glacier and basin averages of 1.94 and 1.15 m in 1967-72 and the long-term estimates of 1.7 and 1.0 m indicate that about four-tenths of the glacier snow is derived from these sources.

Conclusions

Maclure Glacier and other small glaciers in the Sierra Nevada survive in the present climatic regime because of favorable high-altitude topography and mean annual precipitation that equals ablation on the average. The precipitation is amplified by prevailing southwest storm winds that drift snow into the steep-walled north-facing amphitheaters in which the glaciers exist.

The 6 years of available data show that the present glacier mass is sensitive to changes in annual precipitation. An average depth of 1.2 m of water equivalent was added to the glacier in the heavy snow year of 1967 and 0.7 m in 1969. Precipitation both years was much above average in the Central Valley of California based on 100 years record. A series of such above-average years would cause a dramatic increase in the mass of Maclure Glacier. The 1968 and 1972 years had below-average precipitation and an average depth loss of 0.8 m of water equivalent from the glacier each year. A succession of below-average precipitation years would cause a large shrinkage of glacial *ice.* The loss would be accelerated by the lower albedo of exposed ice and firn.

Annual runoff from the Maclure Creek basin fluctuated much less than annual precipitation. The basin accumulated 2.0 m of snow-water equivalent in 1967 but only 0.6 m in 1968. Yet, total runoff depth was 1.5 m in 1967 when an average of 0.4 m of water was stored over the basin, and 0.9 m in 1968 because of the melting of 0.3 m of old ice and firn over the basin. The small Sierra Nevada glaciers provide natural cyclic water storage that smooths fluctuation in precipitation. Practically all runoff from the Maclure Glacier basin occurs during the June-September period when it is beneficial in sustaining downstream flow.

Six years of data represent only a point in glacial time. Hopefully, the IHD data for Maclure and other glaciers will lead to some meaningful conclusions about global climate and the relation of glaciers to climate.

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