Physical and Chemical Description of Birch Creek a Travertine Depositing Stream, Inyo County California

Physical and Chemical Description of Birch Creek a Travertine Depositing Stream, Inyo County California

By KEITH V. SLACK

LIMNOLOGICAL STUDIES

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

CONTENTS

ILLUSTRATIONS

TABLES

LIMNOLOGICAL STUDIES

PHYSICAL AND CHEMICAL DESCRIPTION OF BIRCH CREEK, A TRAVERTINE DEPOSITING STREAM, INYO COUNTY, CALIFORNIA

By Keith V. Slack

ABSTRACT

Birch Creek, a small stream with headwaters in the White Mountains of eastern California, was studied during the spring of 1961 and the summer of 1962 to determine the environmental controls on travertine deposition. Although in an arid region and ephemeral for most of its length, Birch Creek has perennial flow which starts with ground-water discharge in a wet meadow and continues for about 1¼ miles before disappearing into valley alluvium. In 1961, travertine occurred as isolated hummocks of calcite associated with algal colonies just downstream from the wet meadow and increased in abundance downstream with increasingly abundant plant life. In the spring of 1962, from 4 to 8 inches (10–20 cm) of streambed material, including algae and ¾–1¼ inches of travertine crust, was scoured away by high flow resulting from unusually heavy precipitation in February and May. Travertine is estimated to form at the maximum rate of 5–10 mm per year, as determined from deposits on plexiglass plates. Thus, the eroded travertine may have represented 4–6 years accumulation.

Water properties varied daily, with downstream distance, and between the two periods of study. Ground water emerged supersaturated with respect to calcite and carbon dioxide. Calcite was precipitated as water flowed downstream, resulting in decreased concentrations of solutes, chiefly free carbon dioxide, bicarbonate, and calcium ions. Dissolved oxygen concentration was inversely related to water temperature, but in 1961 when algae were abundant, percent saturation was higher during the day and lower at night than in the following year. This is interpreted to have been the result of greater photosynthesis and respiration in 1961. There were also differences in concentrations of calcium and bicarbonate ions and of free carbon dioxide between years. The magnitude of daily variations in physical and chemical properties of the stream and its surroundings increased downstream. Short-term changes in water composition were most frequent during daylight at upstream stations.

Separate identification of inorganic and organic controls on travertine genesis is difficult because both factors are directly influenced by solar radiation.

INTRODUCTION

The purpose of this study was to investigate the controls on travertine deposition in a small stream in the White Mountains in eastern California. The relative importance of inorganic and organic agencies in calcite precipitation was of particular interest. The work is part of a continuing program of research on the effects of organisms on properties of natural waters. The study also contributes to knowledge of the physical and chemical dynamics of small streams in arid regions. As demands on available water supplies increase in areas of water deficiency, development of new sources of water becomes urgent. Many small perennial spring-fed streams are potential sources of surface supplies or of water for aquifer recharge. Understanding of the properties of small streams is essential for evaluation of their potential for beneficial uses. Biological research in connection with this investigation will be discussed in a subsequent report. A concurrent study of the geochemistry of the stream was made by Ivan Barnes (1965), to whom I am indebted for certain data.

Travertine precipitation in Birch Creek, Inyo National Forest, Inyo County, Calif., was first reported to the author by B. F. Jones (oral commun., 1960). The stream is a tributary of Deep Springs Valley (fig. 1), a small intermontane basin at an elevation of about 5,000 feet (1,525 m). Hydrology of the valley was described by Jones (1965), and the bedrock geology of the Birch Creek area was studied by Nelson (1963).

Birch Creek (fig. 2) offers many advantages for studying natural processes controlling the composition of flowing water. It is free from cultural influences, is sufficiently small to be studied in detail, and has a wide range of daily variation. Travertine here is an obvious intrastream feature.

SETTING

HYDROLOGY AND GEOLOGY

Deep Springs Valley lies within the White Mountain Range, east of Owens Valley. Precipitation at higher elevations immediately west of Deep Springs Valley enters the ground and reappears as springs which give rise to small streams flowing generally southeastward. Surface flow persists for varying distances over which water is lost by evapotranspiration and to ground water through the channel. The water ultimately seeps into valley alluvium to discharge near the playa (Jones, 1965).
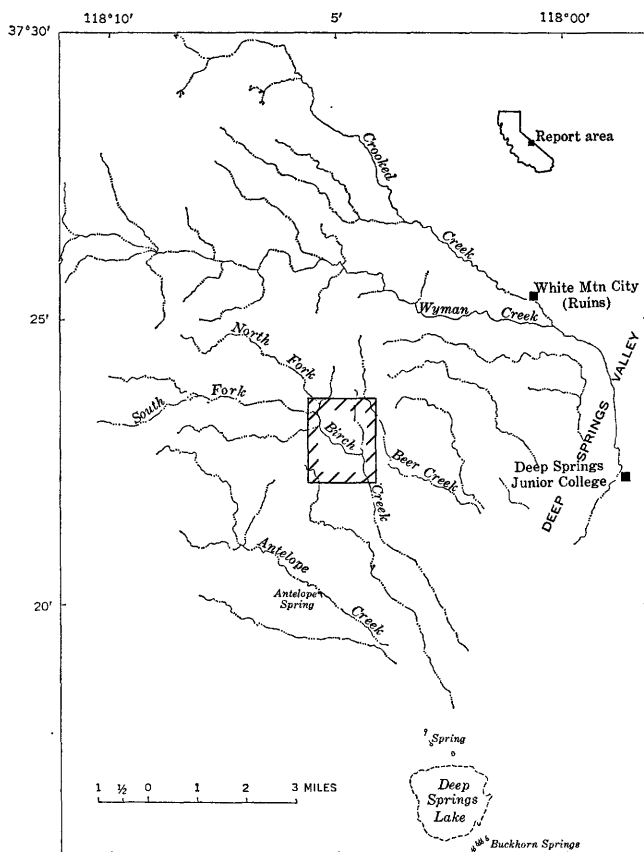
FIGURE 1.—Birch Creek and Wyman Creek drainages.

Birch Creek is intermediate in length and discharge between two other tributaries of Deep Springs Valley: Antelope Creek (smaller) and Wyman Creek (larger). Birch Creek drains an area of 16 square miles (41 sq km). The channel begins at an elevation of 10,000 feet (3,048 m) and extends to the alluvial fan at an elevation of 5,600 feet (1,700 m), and it is ephemeral for most of its length. Perennial flow originates with ground-water discharge at an elevation of 6,950 feet (2,118 m) and continues until losses to the ground and to evapotranspiration exceed the supply. In 1961, this distance was about 1¼ miles (2 km); the following year it was about 1¾ miles, or half a mile (0.8 km) farther, the result of an exceptionally wet winter and spring. Outflow from the springs was relatively uniform; discharge in May 1961 and July 1962 was between 0.4 and 0.5 cfs (cubic feet per second). The vertical gradient of the part of Birch Creek having perennial flow averages 376 feet per mile (71 m per km).

Bedrock is metamorphosed sedimentary rocks of Cambrian and Precambrian age, locally intruded by granite. Below the confluence of the North and South Forks, Birch Creek Canyon cuts through granitic rocks and contact metamorphic rocks (calc-silicate hornfelses,

marbles, quartzites, and schists). Small zones of sulfide minerals and their alteration products are abundant in the drainage.

Although travertine cementation of bed material was observed in Antelope Creek and in a few places in Wyman Creek, a striking example of travertine formation was afforded by Birch Creek. Contact of ground water with calcite and dolomite above the headwater springs of Birch Creek accounts for the high calcium concentrations in the stream.

The largest tributary of Deep Springs Valley is Wyman Creek, whose drainage area is about 30 square miles (78 sq km). Wyman Creek rises in a series of wet meadows above the contact zone between granitic rocks and Precambrian metasediments and flows for about 7 miles in a well-defined channel heavily shaded by brush. Just below the White Mountain City ruins, Wyman Creek is diverted into an irrigation canal leading to Deep Springs Junior College in the valley.

CLIMATE

The study area is in the desert region of southeastern California. Precipitation falls as either rain or snow, and summer thunderstorms are common. Generally, winters are wetter than summers in the White Mountains. The high Sierra Nevada to the west intercepts much of the atmospheric moisture which otherwise would reach the drainage of Deep Springs Valley.

Kesseli and Beaty (1959) found that, for the period of record, nearly three-fourths of the floods in the White Mountains resulted from thunderstorms. Prolonged frontal rains on winter snow cover produced fewer floods. Snowmelt in late spring or early summer caused the least number of floods. The studies also disclosed from one to three major floods per decade and many minor floods in the White Mountains. Streamflow was not appreciably changed by rains during my fieldwork on Birch Creek.

The first field season of this investigation, 1961, was preceded by about 3 years of deficient rainfall in the area. Temperatures averaged below normal in May and above normal in June 1961. During the 1962 field season, precipitation was above normal and temperatures below normal. Unusually heavy snowfall in January, February, and March, followed by a widespread storm on May 14–15, 1962, resulted in high streamflow which greatly affected the Birch Creek channel. Table 1 shows the distribution of precipitation for the two field seasons.

Short-wave solar radiation was intense during the day at the study sites (fig. 3). A maximum of 1.75 g cal per sq cm per min. (gram calories per square centimeter per minute) was measured at 1300 hours on July 20, 1962, at station 3.

Compiled by the Branch of Special Maps,
U.S. Geological Survey, Topographic
Division, Jan. 1963

SCALE 1:10 000

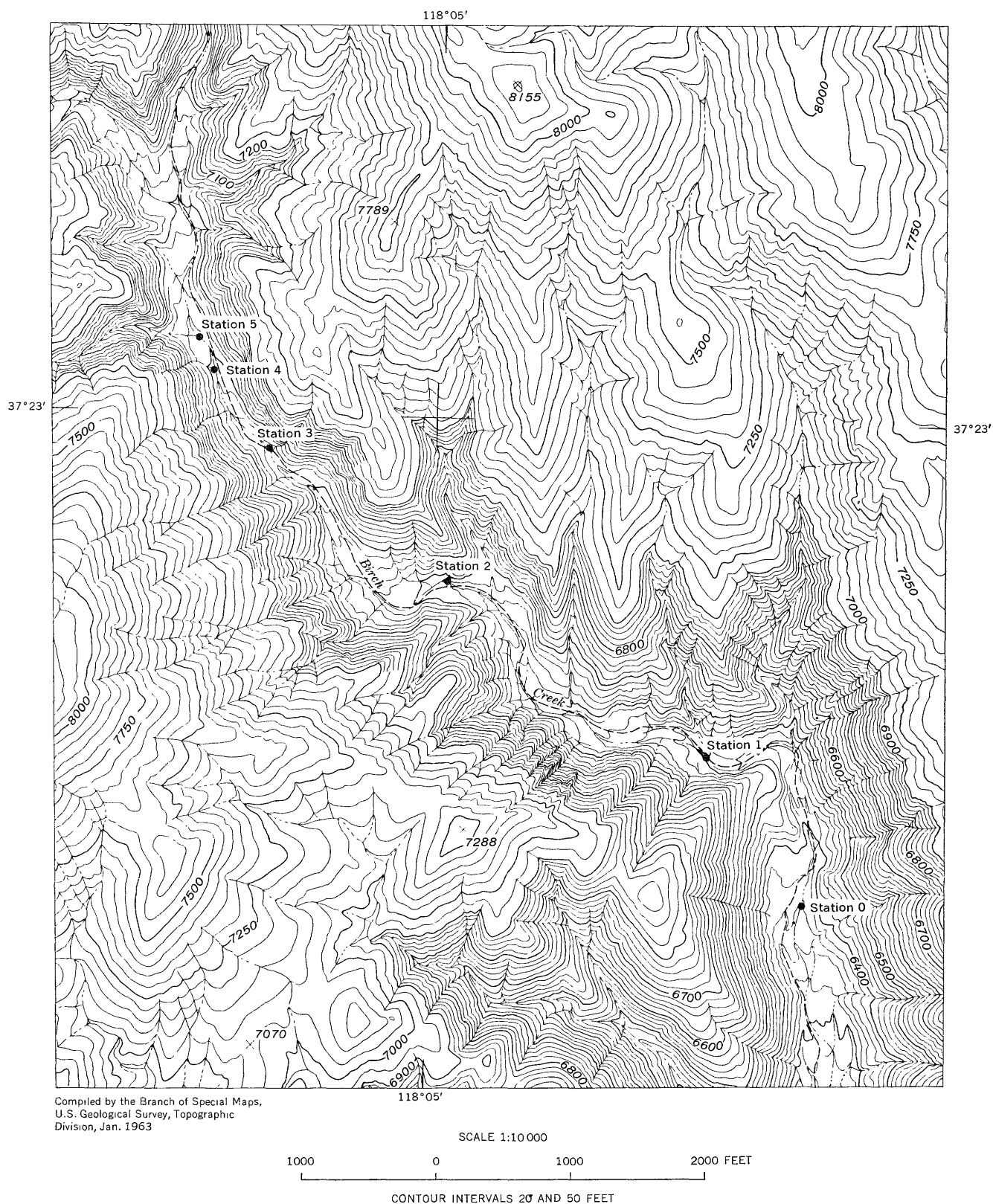1000   0   1000   2000 FEET

CONTOUR INTERVALS 20 AND 50 FEET

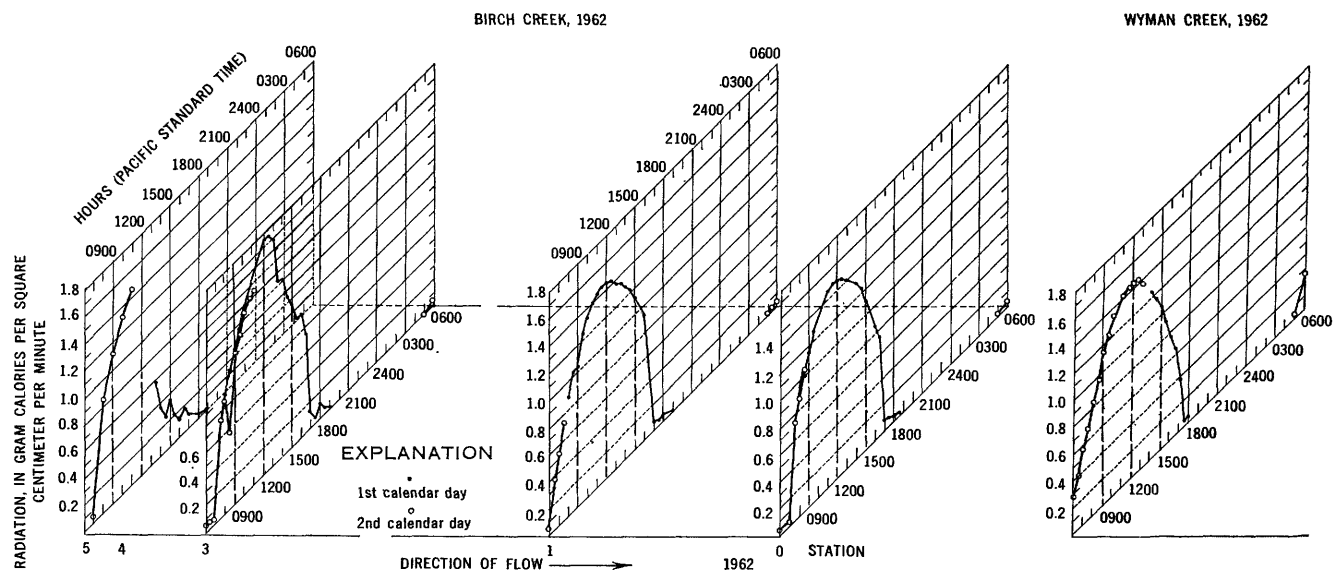FIGURE 2.—Topography of part of Birch Creek, and location of stations.

FIGURE 3.—Daily change in short-wave solar radiation (<3.5 mu) at stations on Birch and Wyman Creeks, 1962.

TABLE 1.—Daily precipitation,[1] in inches, during the 1961 and 1962 field seasons at weather stations [2] nearest to Birch and Wyman Creeks, Calif.

[Observations of stream properties were begun at study stations (in bold face) on dates indicated]

Day	1961						1962							
	May			June			May		June		July		August	
	Weather stations						White Mountains' weather stations							
	Deep Springs Coll.	White Mtns. 1	White Mtns. 2	Deep Springs Coll.	White Mtns. 1	White Mtns. 2	1	2	1	2	1	2	1	2
1				0.17	Trace	0.04								
2					0.10	.04			Trace					
3				**Sta. 4**	.07						Trace			
4			Trace			Trace					Trace			
5		Trace	Trace	**Sta. 3**	Trace									
6		Trace	Trace										**Wyman Creek**	
7		0.03	0.08											
8														
9											Trace	**Sta. 0**	Trace	
10														
11														
12		.04	.09			Trace	Trace	0.10			0.08	0.20		
13			.04				0.14	.36			1.04	1.20		
14							1.52	2.10	0.13	0.10				
15		Trace					.80	1.00	.50	.90	Trace	**Sta. 1**	Trace	
16							.58	.54	.13	.10	.15	Trace	Trace	
17		Trace					.61	.08	Trace	Trace				
18						Trace								
19		Trace					Trace	Trace						
20		Trace										**Sta. 3**		
21						Trace	.26	.27			Trace			
22						Trace					Trace			
23	**Sta. 1**					Trace					Trace			
24								.08			.40	**Sta. 5**		
25						Trace	Trace	.12			.30			
26	**Sta. 5**					Trace	.08	.09						
27							.15	1.46			Trace			
28							.24	.52			Trace			
29	0.03	.03	Trace								Trace			
30	.04	.14	.40					.03						
31		.04	Trace				Trace							
Total: in	0.07	0.28	0.61	0.17	0.17	0.08	4.38	6.75	.76	1.19	1.97	1.40	Trace	
mm	18	72	155	43	43	20	1112	1713	193	302	500	356	Trace	

[1] U.S. Weather Bur. (1961, 1962).
[2] Elevations, distances, and directions of weather stations from sta. 1, Birch Creek: Deep Springs Coll., 5,225 ft (1,593 m), 5.4 miles (8.7 km) east; White Mtns. 1, 10,150 ft (3,094 m), 10.6 miles (17 km) northwest; White Mtns. 2, 12,470 ft (3,801 m), 16.9 miles (27 km) north-northwest.

METHODS

Daily and spatial changes of environmental properties were studied during the spring of 1961 and the summer of 1962. Detailed observations were made at a single point on the stream for 24–30 hours, usually with a lapse of several days between successive study periods. The resulting nonsynoptic data cannot be compared in detail, although they probably permit general comparisons of conditions at the various stations for each field season. Similar data were recorded at station 1 on successive days in 1962. In 1961, stations 1, 3, 4, and 5 were studied. In 1962, stations 0, 1, 3, and 5 on Birch Creek and one station on Wyman Creek were studied. The reach of channel at station 0 was dry in 1961.

Except as noted, chemical methods used were those of Rainwater and Thatcher (1960). All clock times are given in the 24-hour system referenced to Pacific standard time.

The azide modification of the Winkler method was used to determine dissolved oxygen. Oxygen values were programed for a digital computer, using solubility data of Elmore and Hayes (1960), and corrected for water temperature and atmospheric pressure. To take a dissolved oxygen sample, a 300 ml BOD (biological oxygen demand) bottle was rinsed with stream water, filled, then submerged in the stream to the neck. A plastic tube attached to a water-filled rubber bulb, which was fitted with two-way valves, was inserted to the bottom of the bottle. Air bubbles were carefully excluded. Compression of the bulb expelled about 85 ml of water at the bottom of the bottle and caused the bottle to overflow; relaxation of the bulb refilled the bulb with stream water. In this way the bottle was gently flushed with about 1 liter of water before fixing the sample.

Parameters involved in carbonate reactions were measured by Barnes (1963, 1965), whose data are used here. Stream pH was measured immediately on collection by a two-buffer technique with a Beckman Model N Meter. Electrodes and buffers were maintained at sample temperature by keeping them immersed in the stream between observations. Bicarbonate ion concentration was measured by titrating a 50 ml sample with 0.01639 N sulfuric acid and recording pH and milliliters of acid, starting at the color change of methyl purple and continuing to an observed pH of 4.0. Carbonate and free carbon dioxide concentrations were computed by a digital computer from temperature, pH, ionic strength, and bicarbonate data.

Two-liter samples of water were collected in polyethylene bottles at 0300 and 1500 hours during the daily study at each station. Analyses for major anions and cations were performed in the U.S. Geological Survey's Quality of Water Branch laboratory in Washington, D.C. Ten milliliters of chloroform was added to each sample collected in 1962 to inhibit biological activity, but changes in concentrations of biologically active solutes were not precluded. In 1962, at the times listed above, a second 2-liter sample from each station was filtered through glass-fiber pads, with about 2-mu (micron) retention capacity, and fixed with 10 ml triple-distilled nitric acid for spectrographic analysis (Silvey and Brennan, 1962). Hourly water samples for calcium and magnesium analyses were acidified with concentrated hydrochloric acid to prevent precipitation within the bottle.

The mercurimetric method of Iwasaki, Utsumi, and Ozawa (1952) was used for chloride analyses.

Specific conductance of water at station 0 and on Wyman Creek was recorded in 1962 using battery-powered conductivity recorders with automatic temperature compensation. Although accuracy of the equipment was impaired by calcite precipitation on electrode surfaces in Birch Creek, daily changes in conductance of the water were clearly shown.

A 0 to 10,000-foot (0–3,048 m) aneroid barometer was used for atmospheric pressure measurements in 1962. Pressures were estimated from elevations in 1961.

Solar radiation having wavelengths less than 3.5 mu was measured in 1962 at ½-hour intervals during daylight with a 50-junction Eppley 180-degree pyrheliometer.

In 1961, stream discharge was estimated from the difference in head of water on a ruler first held parallel, then held perpendicular to the flow (Linsley and others, 1949, p. 202). In 1962, a portable V-notch weir was installed at each station on Birch Creek.

During daily observations at individual stations, temperatures of air, water, streambed, and banks were measured with a multichannel thermistor thermometer, accurate to 0.1°C.

Relative humidity in 1962 was measured with an electric hygrometer exposed in the shade 6–12 inches (15–30 cm) above the ground. Relative humidity was not measured in 1961.

The rate of travertine deposition at each station during both field seasons was estimated from material deposited on 4×6 inch (10×15 cm) plexiglass plates and, in 1962, also on 1×3 inch (25×75 mm) glass microscope slides immersed in the stream. The deposits on the plates were dissolved in dilute acid, and the concentration of calcium and magnesium in solution was measused. The rate of travertine accumulation on the glass slides was determined by measuring the average thickness of the deposits.

DESCRIPTION OF BIRCH CREEK

MORPHOLOGY AND FLOW

Birch Creek, like Wyman Creek and many other streams in arid regions, has its greatest discharge near its source (pl. 1). During both years, flow of about 0.5 cfs (14 liters per sec) was measured at the outlet from the wet meadow. Flow diminished downstream, and the water finally disappeared into valley alluvium. Besides the general decrease in discharge downstream resulting from evapotranspiration and loss to ground water, there was also a daily fluctuation in discharge. The maximum discharge was observed between midnight and sunrise; the minimum occurred shortly after noon, probably showing the effect of evapotranspiration on streamflow.

As a result of daily variation in stream discharge, the place where streamflow ceased fluctuated throughout the day during both years of observation. During one 24-hour period in May 1961, the terminus of flow moved 130 feet (40 m) along the channel from a minimum extension at 1400 hours, at the time of maximum air temperature, to a maximum extension at about 0530 hours, 1 hour after the lowest air temperature (fig. 4). Because the wet winter increased water storage in 1962, the stream extended farther down the canyon, and the daily fluctuation in length exceeded that of 1961. Although discharge gradually decreased during the summer of 1962, the stream was about half a mile (0.8 km) longer in August 1962 than in June 1961.

Headwater springs were probably the source of nearly all the flow in Birch Creek during the study periods, but there was evidence that discharge increases rapidly in response to showers in the drainage basin, either owing to accretion of water, reduced losses, or both. In 1961, Birch Creek had two periods of lengthened surface flow, both following rains. In 1962, following each of several periods of showers, specific conductance at station 0 and on Wyman Creek decreased, a result of dilution (fig. 4).

STATION DESCRIPTIONS

Data were collected at six stations on Birch Creek and one on Wyman Creek. The same kinds of data were not collected at all stations.

Station 5.—The headmost station on Birch Creek was at the outflow of the wet meadow, immediately downstream from the last of several seeps issuing from the right bank. Stream width averaged 30 inches (76 cm), and depth averaged 2–4 inches (5–10 cm). A dense growth of horsetail (*Equisetum*) covered the 3-foot (1 m)-high banks. The reach was shaded by small birch (*Betula*) and willows (*Salix*), the fine roots of which were exposed in eroding banks. Watercress

(*Nasturtium*) was present near the seeps. The rocky streambed was largely uncemented by travertine. In 1961, numerous calcite hummocks 1–3 mm in diameter were present on rocks at or slightly above the waterline. These appeared to be remnants of former *Rivularia* colonies, and a few living examples of this blue-green alga were present in the same zone. In 1962, no calcite was evident on the rocks, although a band of living *Rivularia* extended from three-sixteenths of an inch (0.5 cm) above to 1 inch (2.5 cm) below the waterline. Both here and at station 4, very old piles of axe-cut brush were the only evidence of human interference. Because brush growing on the banks was about the size of the old cuttings, cultural effects on the stream were considered to be negligible.

Station 4.—A second station was established 83 yards (76 m) downstream from station 5. The stream was about the same size, although more exposed because of lower banks and fewer trees and horsetail. Thistles and other riparian annuals were more abundant than at station 5. Calcite deposits were present on most rocks, although not in a continuous sheet, and many rocks could be dislodged by hand. In 1962, many of the calcite deposits exhibited evidence of erosion, and the preexisting cemented bed was largely covered by a thin layer of unconsolidated sand and gravel. Algae and aquatic moss were more abundant than at station 5.

Station 3.—The channel in this reach was nearly as large as at station 4 and exposure was about the same. Willows were less abundant, but where the stream was in contact with the north wall of the canyon, juniper and piñon pine provided some shade. Thistles and horsetail were present, and rabbit brush (*Chrysothamnus*) and sagebrush (*Artemisia*) grew on the banks In 1961, the bed was so completely cemented in this reach that individual rocks were not distinguishable. A year later, bare rock was exposed where large sheets of *Rivularia*-covered calcite 1 cm or more thick were broken away. Algae and moss were much more abundant here both years than at the higher stations. Several falls 20–60 inches (0.5–1.5 m) high were present immediately downstream from this station.

Station 2.—Channel width averaged about 28 inches (70 cm), but the depth was 2 inches (5 cm) or less and discharge was noticeably diminished. Exposure was greater than at station 3. The steep left bank, about 6 feet (2 m) high, supported a sparse stand of piñon pine, although the surrounding vegetation was dominated by sagebrush and other low shrubs. This station was at the downstream limit for horsetail and for nearly all the aquatic moss. *Rivularia* was abundant in 1961 when the channel was completely cemented. In 1962, almost all of the travertine observed earlier
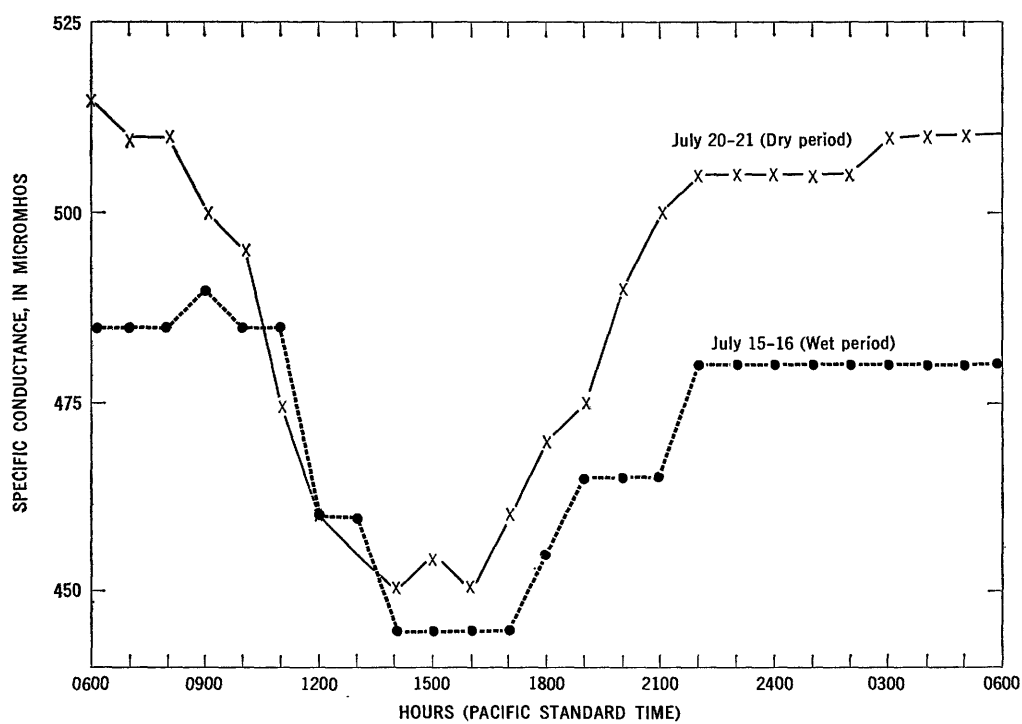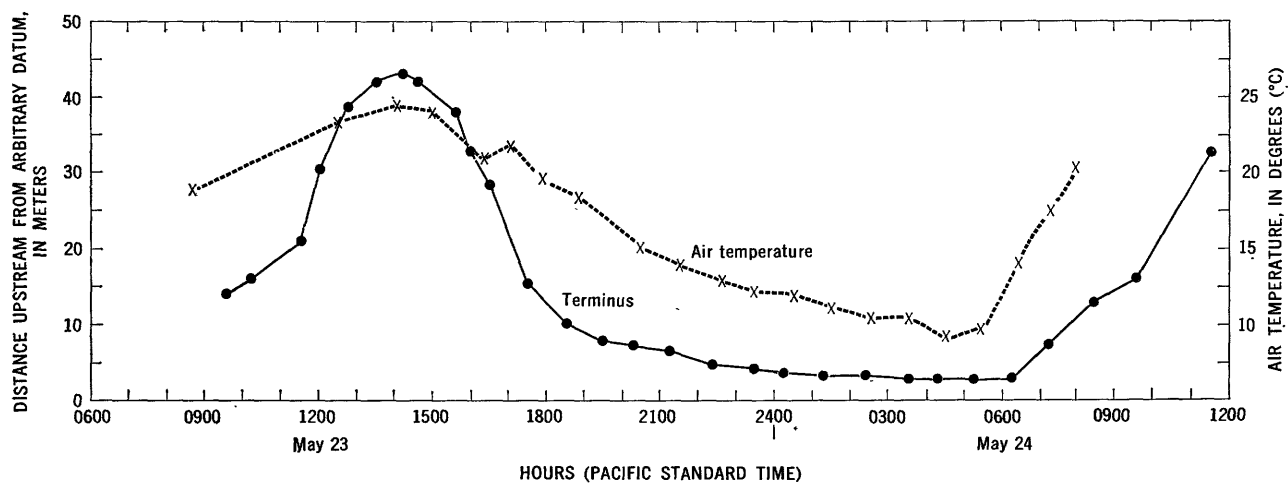
FIGURE 4.—Air temperature at station 1 and terminus of flow, Birch Creek, May 23-24, 1961. Daily change in specific conductance at station 0 during a wet period (July 15-16) and a dry period (July 20-21), Birch Creek, 1962.

had been stripped away, and the bed was composed of unconsolidated gravel and travertine fragments, covered with a film of newly formed calcite. The channel in this locale contained braided reaches.

Station 1.—Birch Creek varied in size at station 1 both daily during observation and between the two periods of observation. In 1961, streamflow terminated a few hundred yards downstream from this station, but in early July 1962, flow continued about half a mile (0.8 km) farther downstream. No shade was provided by the sagebrush, rabbit brush, or other shrubs. In 1961 the bed was completely cemented by a crust of algal-covered travertine. By 1962, the channel was entrenched about 4 inches (10 cm), and the banks were unstable; the gravel bed contained a thin soft discontinuous travertine coating. No calcite-encrusted algae were found in 1962.

Station 0.—This station was established in 1962 on a reach which was dry the previous year. The canyon was wider at this point, but the surroundings and bed conditions were similar to those at station 1.

Wyman Creek.—Data were collected in 1962 at the White Mountain City ruins on Wyman Creek for comparison with Birch Creek data. Stream width averaged 39 inches (1 m), and depth averaged about 5 inches (12 cm). Although a narrow band of willows and other trees 3–10 feet (1–3 m) tall formed dense cover over most of the reach, sagebrush was the dominant plant. Near the water the sand banks were covered by grass, horsetail, and moss. Streambed rocks were cemented with calcitic deposits, and aquatic organisms were abundant. Early in 1962, the riparian vegetation above and below the study area was burned to improve access to the water for range cattle. The study site was not directly affected by the fire, but the reduced amount of shade in upstream burned areas may have affected water temperature and other properties. Sediment which may have resulted from the fire imparted a light-gray appearance to the water. The only cattle observed in Wyman Creek drainage were several miles upstream.

TRAVERTINE

Calcitic deposits from natural waters have long been objects of scientific inquiry by geologists and biologists. Various names are applied to these sediments: marl, tufa, sinter or travertine. According to the classification given by Twenhofel (1950, p. 356, 375), and followed in this report, "marl" is an unconsolidated calcium carbonate sediment; "tufa" and "sinter" are relatively porous deposits, and "travertine" is a compact banded deposit of calcium or magnesium carbonate. This description of travertine most nearly fits the

streambed deposits of Birch Creek, although tufa is also present in association with aquatic moss.

Deposition of calcium carbonate in fresh waters has been attributed both to inorganic and to organic processes. The inorganic processes include all causes for supersaturation with calcite which result in loss of carbon dioxide. Thus, an increase in water temperature lowers the solubility product of calcium carbonate and the solubility of carbon dioxide, increasing the carbonate ion concentration (Johnston and Williamson, 1916; Revelle and Fairbridge, 1957). Evaporation increases the concentrations of calcium ions and carbonate ions. Agitation of water tends to bring about equilibrium between the partial pressures of carbon dioxide in the water and in the atmosphere. When water is supersaturated with carbon dioxide, loss of carbon dioxide to the atmosphere results in precipitation of calcium carbonate.

Organic processes which produce calcitic sediments in fresh waters are removal of carbon dioxide by plants during photosynthesis, accumulation of skeletal and protective parts of organisms, and, possibly, bacterial activity. Photosynthetic uptake of carbon dioxide is the only biological agency of significance to travertine formation in Birch Creek.

It is clear that removal of carbon dioxide from a saturated or supersaturated solution results in deposition of calcium carbonate, regardless of the process responsible for carbon dioxide removal.

DESCRIPTION OF DEPOSITS

Travertine in Birch Creek occurred as isolated nodules of calcite-impregnated *Rivularia* colonies at station 5. Algae increased in abundance downstream, and between stations 4 and 3 the colonies coalesced to form a hummocky consolidated sheet which completely blanketed the streambed in 1961. Travertine farther downstream was smoother where continued calcite deposition obscured the hummocks. Fresh surfaces of the travertine were firm and slippery to the touch, especially in areas of rapid current. Newly formed travertine on fresh surfaces was coarsely granular or tuftlike in appearance.

Travertine markedly influences stream morphology where the rate of travertine deposition exceeds the rate of erosion. Gregory (1911) cited examples of waterfalls in Yugoslavia which advanced downvalley as the result of travertine deposition on their surfaces. Macfayden (1928) described a Swiss stream that flowed on a ridge of tufa deposited by aquatic moss. In Birch Creek, masses of calcite, calcite-cemented plants, and litter form riffles or accumulate in pools and cause water to spill over the top. Although accreting obstructions

frequently break away, several examples were noted where flow was diverted by calcitic obstructions. Minckley (1963) reported a similar condition in a Kentucky stream. Abandoned channels were observed in the middle reaches of Bich Creek, where the active channel was 3 feet (1 m) higher than a parallel, abandoned channel.

The reach between stations 2 and 3 in May and June 1961 had many pools containing incipient concretions in process of enlargement. Each concretion examined had an organic nucleus: a twig, pine cone, willow inflorescence, or leaf—each encased in granular travertine whose external form reflected the form of the central object. Several small pools were present behind piles of travertine-cemented willow litter. Other calcitic deposits had accumulated on exposed tree roots or on stems of horsetail, grass, or moss growing in the water. The "moss" deposits, like the "petrified moss" described by Twenhofel (1950, p. 375), was porous tufa which reflected the coarse structure of stems and leaves on which the calcareous substance had precipitated. Moss tufa commonly formed small riffles in the middle reach of Birch Creek.

BIOLOGICAL CONSTITUENTS

Travertine is calcium carbonate deposited upon and within an organic substrate. Sediment particles of various kinds become imbedded in the travertine as it forms. If samples of Birch Creek travertine are decalcified in dilute acid, the spongy mass which remains has the size and shape of the original sample. The residual mass is composed largely of algal filaments and moss. Similar observations were reported by Roddy (1915), Howe (1931), Fritsch (1949), and others. In Birch Creek travertine, as in the deposits studied in the cited reports, blue-green algae (Myxophyceae) were dominant, but the genera were different. The most abundant algae in the travertine deposits in Birch Creek were members of the family Rivulariaceae.

The hemispherical or irregularly-shaped colonies of *Rivularia* were especially abundant. Each colony contained numerous radially arranged filaments which were attenuated from base to apex. Crystalline aggregates of calcite occurred with the mucilage between the filaments, resulting in an indurated mass which had concentric stratification. Living filaments occurred only in the outer stratum, as was also reported by Weed (1889, p. 649) and by Fritsch (1945, p. 840). Several biologists have noted the absence of carbonate deposits on other types of algae growing adjacent to calcite-depositing species (Fritsch, 1945, p. 869; Lewin, 1962, p. 463). These scientists have suggested that mucilaginous sheaths surrounding the filaments of calcite-

depositing algae are involved in the formation of the crystalline deposits.

The presence of living algae within fresh travertine in Birch Creek was indicated by the color of the deposits, which varied from place to place. The streambed travertine observed in 1961 ranged from brown near the headwaters to red in downstream reaches. Recently formed travertine on newly exposed surfaces was yellow or tan. In splash zones of heavily shaded falls, massive rounded deposits of travertine were yellow or orange. The underwater parts which were shaded were pale green.

INORGANIC COMPOSITION

Chemical and crystallographic characteristics of travertine samples were investigated. X-ray studies of streambed travertine and of deposits formed on glass microscope slides that had been immersed in Birch Creek in 1962 showed only calcite composed of almost pure calcium carbonate. The maximum magnesium content of 2 percent, based upon unit cell dimension, is within the range of unit cell dimensions for pure calcium carbonate (R. G. Wolff, Ivan Barnes, and Daniel Appleman, oral commun., 1964). In contrast to results of the X-ray studies, the proportion of calcium to magnesium in deposits on plexiglass plates increased downstream during both years (table 2). It is tentatively concluded that downstream enrichment of magnesium in plate deposits resulted from the settling out of magnesium-rich sediment.

TABLE 2.—*Weights and relative proportions of calcium and magnesium in deposits from clear plexiglass plates immersed in Birch and Wyman Creeks, Calif.*

[The period of immersion was 18 days in 1961 and 34 days in 1962]

Station	1961			1962		
	Weight Ca (mg per sq dm per day) [1]	Weight Ca plus Mg (mg per sq dm per day) [1]	Ca: Mg ratio [2]	Weight Ca (mg per sq dm per day) [1]	Weight Ca plus Mg (mg per sq dm per day) [1]	Ca: Mg ratio [2]
5	0.11	0.15	3.1	0.55	0.70	3.5
4	.14	.15	7.8	.01	.02	2.5
3	.89	.96	12.9	1.47	1.50	42.2
2	.34	.35	72.4	15.58	16.12	30.7
1	.92	1.01	10.1	.70	.71	73.6
Wyman Creek	.01	.03	.5	.03	.04	19.0

[1] Area of plate available for deposition of travertine: 338 sq cm.
[2] Milligram calcium per milligram magnesium.

RATE OF FORMATION

An attempt was made to measure the rate at which travertine formed at each station during both field seasons. Plexiglass plates were anchored horizontally on the streambed for 18 days in 1961 and 34 days in 1962. In 1962, racks of glass microscope slides also were immersed at stations 1, 3, and 5 to collect samples of travertine. A simple correlation between calcium and mag-

nesium accumulation on the plates and station location was not expected because of sediment accretion and of differences in the duration and season of exposure between the two years. The data listed in table 2, however, show a general downstream increase in travertine accumulation, which is in accordance with field observations of greater cementation and encrustation of bed materials downstream.

If the total accumulations on the substrates are accepted, and if the weight of calcium at each station is an indication of the amount of calcite, then the average rate of travertine formation was greater in 1962 than in 1961. The larger deposits on plates at lower stations during 1962 may have resulted, in part, from the settling out of detrital travertine. For example, removal of pre-1962 travertine was nearly complete at station 2, where the largest weight increase between years occurred. The different lengths of time that test surfaces were exposed during the two years might have exaggerated the 1962 precipitation rate. Studies of algal attachment on sterile surfaces in water have shown that cell counts increase rapidly following an initial lag of several days (Yount, 1956; Odum, 1957). For short periods, doubled exposure time will, in general, result in a more than doubled biomass. A similar relationship may be expected for algal-precipitated calcite.

The greatest thickness of travertine deposited on a glass slide in Birch Creek was 1 mm in 34 days at station 3. Thus, a maximum deposition rate of $\frac{3}{16}$–$\frac{3}{8}$ inch (5–10 mm) of travertine per year appears probable, a rate consistent with values reported by Pollock (1919) and Blum (1960). This rate is much slower than the 25 mm per year indicated for Doe Run, Ky. (Minckley, 1963, p. 37), or the $\frac{1}{20}$–$\frac{1}{16}$ inch (1.25–1.5 mm) in 3 days reported for the Mammoth Hot Springs, Yellowstone National Park (Weed, 1889, p. 644).

EROSION

Between the 1961 and 1962 field seasons, significant hydrologic activity occurred in Birch Creek Canyon. High flow, following a wet winter and spring, resulted in marked erosion of the channel. Little effect was seen above station 3, but below station 3 nearly all the travertine crust was removed. Remnants of travertine indicated removal of bed material to a depth of 4–8 inches (10–20 cm).

The hard travertine crust of Birch Creek acts as a protective armor over the unconsolidated gravel and sand of the bed during normal flows, but once the protective sheet is breached, the crust is undermined and scoured away. This scouring was observed in 1962 in several plunge pools below small falls between stations 2 and 3. In each pool, an area of uncemented gravel was exposed in the impact zone of the falls.

Size of the scoured area increased as the crust was undercut and fragmented; the broken-off pieces were soon reduced to gravel-sized or smaller particles. But even as the old crust was being stripped away, a new layer was forming. At station 1, individual pebbles were clearly visible, but the bed was so well cemented that the pebbles could scarcely be pulled out by hand. This incipient crust had the familiar tan color and granular appearance of fresh travertine.

Widespread travertine erosion presumably began with increased discharge, which occurred possibly as late as May 1962 because erosion during July and August was continuous. Dissolution of calcite did not occur during the observation period because the stream was supersaturated with respect to this material. If surface runoff of dilute snowmelt occurred, then dissolution may have been a primary cause of crustal breakup. The abundance of woody and herbaceous plants growing on the banks and even in the water of the stream indicated that erosion was largely confined to the stream channel. Lack of erosion outside the stream channel is evidence against the possibility of direct snowmelt runoff and, hence, against the dissolution of calcite.

The fact that erosion was minor above station 3 supports the view that travertine erosion there was primarily mechanical rather than chemical. A short distance below station 3, large boulders gave rise to several small falls. High flow capable of breaching the crust would have had less effect above this nickpoint because of limited downcutting. However, chemical erosion by water unsaturated with respect to calcite should have extended above such obstructions. There was no indication that flow from a tributary caused channel erosion. The rate of erosion in early summer 1962 was such that removal of pre-1962 crust must have been virtually complete in the affected places.

The frequency of periods of travertine erosion in Birch Creek is unknown, although floods of sufficient magnitude to be remembered by local observers have occurred in the past. In 1952 a flood damaged a section of State highway through Deep Springs Valley and destroyed an unimproved road which formerly followed Birch Creek and the North Fork. Long stretches of the unimproved road have disappeard, and at one point where the road crossed the creek between stations 1 and 2, the roadbed is 10 feet (3 m) above present stream level. Traces of streambed travertine on outcrops more than 3 feet (1 m) above the present bed also attest to general cutting in Birch Creek Canyon. In 1961, the streambed crust below station 2 was $\frac{3}{4}$–$1\frac{1}{4}$ inches (2–3 cm) thick. This crust is believed to have formed in 4–6 years. Erosion of bed material from

Birch Creek in 1962 supports the observations of Lustig (1965) and others of widespread cutting of canyon fill in western United States.

ENVIRONMENTAL MEASUREMENTS

The shallow turbulent flow of Birch Creek exposes a large amount of water surface per unit volume to the atmosphere and to the streambed. Thus, it was of interest to know how the external environment varied during the times when stream properties were being studied. Air and substrate temperatures were measured during both years. In 1962, atmospheric pressure, relative humidity, and short-wave solar radiation were determined, in addition to water properties.

RELATIVE HUMIDITY

Relative humidity was generally below 30 percent except during rain showers. Maximum and minimum values for each daily study period in 1962 are given in table 3. In general, maximums occurred about sunrise and minimums between 1300 and 1700 hours at each station.

SAND MOISTURE

During the day the sand surface along the streambanks was dry, but at night a zone of moisture moved outward from the water's edge until the banks were damp as far as 15 feet (5 m) away. The upper limit of visibly wetted sand moved downward during the day. Observations were made on sand 3 feet (1 m) from the stream edge at station 3. At 0500 hours the sand was visibly wet from the surface down; at 0900 hours the upper limit of visibly wet sand was 1 inch (2.5 cm) below the sand surface; and at 1300 hours the upper limit was more than 2 inches (5 cm) below the sand surface.

The nocturnal increase in sand moisture probably resulted from lower evaporative losses of water leaking through the bed and banks. Higher water levels at night also increased the water supply to the banks.

TABLE 3.—*Summary of daily changes in relative humidity, Birch and Wyman Creeks, Calif., 1962*

[Rain showers affected maximum values at stations 1 and 5]

Station	Date	Relative humidity (percent)		
		Maximum	Minimum	Average
5	July 24–25	83	27	53
3	July 20–21	45	8	22
1	July 15–16	46	15	29
0	July 9–10	37	7	16
Wyman Creek	Aug. 6–7	20	6	12

AIR TEMPERATURE

Water temperatures and evapotranspiration rates are affected by air temperatures; microgradients of air

temperature occur near the ground because of atmospheric turbulence and of heat transfer to the air by conduction, convection, and radiation. In table 4, air temperatures near the water surface are compared with temperatures of free air a few yards away. Near-water air temperatures were between the free-air temperatures and the water temperatures during the day. Although the maximum daily near-water air temperatures were generally closer to the maximum water temperatures, minimum near-water air temperatures were closer to the minimum free-air temperature. In summary, water temperature had a causal relationship with temperature of the adjacent air during the day. At night, however, temperature of the air layer 1–2 inches above the water surface was under the same control as free-air temperature.

Some variation in air temperatures between stations was due to differences in elevation. Minimum free-air temperatures were lower upstream, and maximum free-air temperatures were higher at downstream stations (pl. 1). Warming in the morning occurred more rapidly than cooling at night.

Short-term fluctuations in air temperature occurred during the afternoon as gusts of hot air blew up the canyon from the valley. Rapid temperature changes also were occasionally observed at night. For example, temperature at station 1 (1962) between midnight and 0100 hours increased 1.5°C, then decreased 3.5°C in the next hour. At station 5 (1962) air temperature suddenly reversed a downward trend and rose 3.8°C between 1900 and 2100 hours. At 2300 hours the temperature was 0.3°C higher. From 2300 hours until sunrise, air temperature fell. Simultaneous changes in the same direction occurred in near-water air temperatures. Short-term reversals in daily air-temperature cycles probably result from local changes in airflow or cloud cover.

As can be seen in table 4, rates of air-temperature change were slightly larger and the range greater in 1962 than in 1961, in contrast to observations of water temperature. For both years the daily range of free-air temperature exceeded the daily range of water temperature at all stations.

WATER TEMPERATURE

In the continuously varying Birch Creek environment, water composition is influenced both by instantaneous water temperature and by the rate at which water temperature changes. Properties which are functions of water temperature are density, viscosity, solubility of solids and gases, evaporation rate, and the metabolism rate of aquatic organisms. Equilibrium between temperature-dependent reactions and environ-

Table 4.—Summary of daily changes in air and water temperatures at various locations, Birch and Wyman Creeks, Calif., 1961 and 1962

Station	Date	Air temperature (°C) Maxi-mum	Mini-mum	Maximum change (°C per hr) In-crease	De-crease	Water temperature (°C) Maxi-mum	Mini-mum	Maximum change (°C per hr) In-crease	De-crease	Microenvironment Station	Date	Distance from water's edge (cm) Hori-zontal	Ver-ti-cal	Type material	Temperature (°C) Maxi-mum	Mini-mum	Maximum change (°C per hr) In-crease	De-crease
1961																		
5	May 26-27	21.1	2.2	---	*3.6	15.6	11.9	*1.0	*0.9									
4	June 3-4	23.9	8.3	11	3	16.7	11.7	2.0	1.4	4	June 3-4	23	4	Sand (1 cm depth)	25.5	8.7	4.6	4.5
												145	20		27.9	7.0	7.4	3.8
3	June 5-6	23.6	9.4	8.9	4.4	18.6	11.4	1.9	1.7	3	June 5-6	42	9		27.1	8.3	6.3	5.3
												110	28		36.8	8.6	10.5	7.6
1	May 23-24	24.5	9.0	6.2	3.4	26.1	6.1	4.2	4.2									
1962																		
5	July 24-25	23.8	9.9	6.4	4.0	14.9	12.9	0.7	0.5	5	July 24-25	85	100	Litter (2 cm depth) on sand.	16.6	12.3	2.8	0.4
												0	-10	Spring water	13.6	13.0	.2	.1
												---	2-3	Air	17.8	10.0	2.7	1.4
3	July 20-21	27.7	10.8	11.2	5.3	17.1	12.1	1.3	1.1	3	July 20-25	9	0	Wet sand (1 cm depth).	26.9	9.2	9.2	4.0
												200	30	Dry sand (1 cm depth).	51+	12.2	18.7	13.6
												---	3	Air	24.6	10 6	8.4	5.4
1	July 15-16	28.6	12.7	5.8	3.6	27.0	10.9	3.3	3.4	1	July 15-16	163	38	Dry sand (2 cm depth).	42.7	12.9	7.0	8.2
												---	---	Bed material	26.9	10.9	3.4	3.3
												---	3	Air	26.1	11.9	2.8	2.2
0	July 9-10	29.1	13.3	7.6	3.0	27.3	9.6	4.5	3.6	0	July 9-10	10	5	Wet sand (2 cm depth).	28.5	9.3	6.2	4.4
												130	15	Dry sand (2 cm depth).	48.1	14.4	9.5	5.6
												---	---	Bed material	27.6	9.6	6.0	2.8
												12	4	Damp sand (2 cm depth).	28.6	10.5	4.7	4.9
Wyman Creek.	Aug. 6-7	34.3	11.1	5.5	6.9	18.7	10.0	1.7	1.0	Wyman Creek.	Aug. 6-7	97	25	Dry sand (2 cm depth).	47.1	11.5	8.7	7.0
												---	6-7	Air	24.7	11.5	4.2	4.0

*Estimated.

ment must rarely, if ever, be reached in shallow turbulent streams like Birch Creek. Nevertheless, conditions of quasi-equilibrium are probably most closely approached at night during periods of uniform water temperature.

Because it was shallow, Birch Creek responded rapidly to changes in solar radiation. Daily variation in water temperature during both years was least at station 5, just below the wet meadow, and greatest at the terminal station downstream (pl. 1). Temperature of the water lagged slightly behind that of the air, but maximum and minimum air and water temperatures occurred at nearly the same times at all stations. Minimums occurred between 0300 and 0530 hours; maximums, between 1100 and 1400 hours. Temperature extremes increased with distance downstream. The greatest 24-hour temperature change recorded was 20°C at station 1 in 1961.

The hourly rate of water-temperature change varied with time of day and with station location (table 4). Warming occurred slightly more rapidly than cooling, in accord with changes in air temperature. Maximum warming rates occurred several hours after sunrise, usually between 0800 and 1100 hours. Maximum cooling rates occurred between 1400 and 1700 hours, well

before sunset. In 1962 at station 5 the water temperature increased 0.7°C between 0900 and 1000 hours. Maximum cooling of 0.5°C occurred between 1300 and 1400 hours. During the same year at station 0 the maximum rate of warming was 4.5°C between 0800 and 0900 hours, and the maximum rate of cooling was 3.6°C between 1600 and 1700 hours.

In 1961 all stations had higher hourly rates of water-temperature change and greater daily ranges of water temperature than in 1962. Air temperatures in July and August 1962 were higher than in May and June 1961. Less variation in water temperature during the 1962 study period probably resulted from higher streamflow and from greater shading by more fully grown annual plants.

MICROENVIRONMENTAL TEMPERATURES

Temperatures were measured at several points in the near-stream environment during 24-hour studies (table 4). Sand temperature varied with solar radiation and with moisture content. Wet sand, cooled by evaporation, was cooler than the air both night and day. Temperature of wet sand corresponded reasonably well to that of water, although temperature extremes of sand exceeded those of water. Dry sand was much warmer

than air during the day and slightly warmer than air at night. No effect of nocturnal fluctuations in air temperature was detected in sand temperature. Temperatures within the bed material at stations 0 and 1 followed water temperature very closely. Thus, most of the aquatic biota were exposed to daily temperature changes which increased in magnitude downstream.

CHEMICAL QUALITY

The lack of synoptic data limits interpretation of the chemical dynamics of Birch Creek. The water exhibited wide daily variations in certain chemical properties, and the range of variability increased downstream. In addition, there was a difference in water compositions between the two seasons of study. The differences between the 1961 and 1962 data may be related to greater discharge in the second year and to the concomitant decrease in photosynthesis and respiration in 1962 because of the loss of much of the benthic algae.

pH

Birch Creek water was alkaline; the pH exceeded 8.0 everywhere except at station 5. Although pH varied from hour to hour (pl. 1), daylight values were generally higher than night values, and downstream values were higher than upstream values. Barnes (1965) ascribed the random variability in pH to sporadic calcite precipitation and to carbon dioxide loss through inorganic and organic agencies. The diurnal pH variation of Wyman Creek water was, in general, like that of Birch Creek.

BICARBONATE

Both daily and spatial variation in bicarbonate ion concentration (HCO_3^-) occurred in Birch Creek. Concentrations decreased from maximum values at station 5 to minimum values at the lowermost station. The daily patterns of change at stations near the downstream terminus of flow are closely comparable for the two years (pl. 1). The 1961 station 1 and 1962 station 0 daily curves show high concentrations at night and low concentrations in the afternoon, an effect which was progressively less pronounced upstream. However, at all stations except station 5, HCO_3^- decreased shortly after sunrise as photosynthesis increased. The early morning decline in HCO_3^- concentration was accentuated downstream and was greater in 1961 than in 1962. Station 5 data are incomplete, but daylight values appeared higher in 1962 than in 1961; night values were the same in both years. Concentrations in the stream below station 5 were higher in 1962 than in 1961, and these differences increased downstream. Possibly the lower average concentration and greater daily range in HCO_3^-

in 1961 were related to the more abundant algal population in that year.

Wyman Creek exhibited a smaller daily change in HCO_3^- concentration, but the same pattern as Birch Creek. A downstream decrease in HCO_3^- concentration was indicated by samples taken half a mile (0.8 km) upstream from the study site.

FREE CARBON DIOXIDE

The variation in concentration of free carbon dioxide (CO_2) strongly reflected changes in pH, as it exhibited a peculiarly erratic and unexplained distribution in time that was generally the inverse of that of pH (pl. 1).

In 1962, concentration of free CO_2 was greater throughout Birch Creek, and the daily range less than in 1961. Although data from station 5 are incomplete, CO_2 values were considerably higher in 1962 than in the previous year. The generally higher and more uniform CO_2 concentrations at other stations in 1962 is interpreted to have resulted from the combination of higher concentrations from the source, decreased photosynthesis, and (Barnes, 1965) ground-water inflow along the entire creek from temporary unsaturated bank storage.

Biological effects on free CO_2 can be seen in the daily curves for Birch and Wyman Creeks (pl. 1). Minimum CO_2 concentrations occurred during the day, when photosynthesis was taking place. Maximum values occurred at night or in the very early morning, when CO_2 was not being utilized by plants but respiratory CO_2 was being added by the aquatic biota. In the absence of photosynthesis, free CO_2 would have been lost to the atmosphere as the water temperature increased during the day. However, because no known inorganic control can cause the undersaturation observed during the day at station 1 (1961), CO_2 utilization by photosynthesis is the most reasonable explanation.

CARBONATE

Concentration of the carbonate ion (CO_3^{-2}) reflected the instability of pH. Downstream increase in CO_3^{-2} was observed both years; maximum values occurred during the day, and minimum values occurred at night (pl. 1). Concentrations at all stations were greater in 1961 than in 1962.

Birch Creek was supersaturated with CO_3^{-2} with respect to calcite at all stations during both years (Barnes, 1965). The degree of supersaturation was greater in 1961 than in 1962, which may indicate a greater rate of travertine formation in 1961.

CALCIUM

The calcium ion (Ca^{+2}) concentration (pl. 1) followed a pattern similar to that for HCO_3^-. The concentration of Ca^{+2} decreased downstream and its daily range increased downstream because of calcite precipitation.

SPECIFIC CONDUCTANCE

Specific conductance is a function of solution concentration and temperature. During 1962, specific conductance was monitored continuously at station 0 to investigate changes occurring daily and over longer time intervals. A daily fluctuation in conductance was clearly shown. The record of long-term changes was unreliable because of calcite precipitation on electrode surfaces.

One might expect evaporation of water from a desert stream to result in higher conductance during the afternoon as solutes become concentrated. Any effect of solute concentration on the conductance in Birch Creek was overshadowed by the effect of solute loss resulting from photosynthesis and other causes of decreased bicarbonate ion concentration. Figure 4 shows that minimum conductance occurred from 1400 to 1700 hours, the time of maximum water temperature; maximum conductance occurred from midnight through the morning hours. Conductance invariably decreased in the morning when the water temperature increased. The effect of temperature variation on specific conductance was compensated for by the recording equipment so that only variations resulting from changed ion concentration were measured.

The daily pattern of specific conductance clearly resulted from precipitation of calcium carbonate, as shown by changes in the bicarbonate and calcium ion concentrations (pl. 1). Thus, conductance measurements support other evidence that the rate of calcium carbonate precipitation in Birch Creek was higher during the day than at night. Average daily range in specific conductance was 84 micromhos between July 18 and August 2, although two very high values that were recorded probably resulted from an obstruction between electrodes of the conductivity cell. Excluding the anomalously high values, average daily range in specific conductance for the most reliable period of record was 54 micromhos, or about 12 percent. Daily variation in conductance of Wyman Creek was similar to that of Birch Creek, but less pronounced.

Specific conductance of Birch and Wyman Creeks decreased during shower periods, probably because of dilution by rainwater.

DISSOLVED OXYGEN

Concentration of dissolved oxygen in Birch Creek was controlled primarily by temperature and secondarily by biological processes. At every station, minimum oxygen concentrations occurred at times of highest water temperatures, and maximum concentrations closely followed the minimum water temperatures (pl. 1). Oxygen concentrations were more variable during the day than at night. For example, at stations 5 and 3 in 1962

the oxygen concentration was uniform from about midnight to 0700 hours; the value at station 3 was 0.6 ppm higher than at station 5. At Wyman Creek a similar period of uniform dissolved-oxygen concentration occurred from 0300 to 0600 hours. Data from both years indicated a transient early morning peak in concentration occurring shortly after sunrise. In 1962 the peak was detected at station 0 at the 0700 hours observation, and on Wyman Creek at the 0800 hours observation. In 1961, peaks were observed at station 1 at 0600 hours and at station 3 at 0800 hours, although the number of samples was not adequate to establish their existence elsewhere. The early morning increase in dissolved oxygen probably resulted from resumption of photosynthesis by algae when water temperatures were low and oxygen concentrations were high from nonbiological causes. Early morning low temperatures slowed the oxygen exchange with the atmosphere so that photosynthetically produced oxygen temporarily increased the dissolved-oxygen concentration.

Daily range in percent saturation of dissolved oxygen increased downstream (pl. 1). Although dissolved-oxygen concentration was inversely related to water temperature, percent saturation with respect to air was slightly higher in the morning than during the afternoon because water temperature increased more rapidly in the morning than it decreased in the evening. The slight undersaturation with oxygen (with respect to air) during the nocturnal periods of uniform dissolved-oxygen concentration might be due either to organic or inorganic causes. Although turbulent flow tends to equilibrate dissolved oxygen with respect to the atmosphere, ground-water inflow and biological respiration tend to bring about undersaturation. Also oxygen-saturated water would dissolve additional oxygen to maintain saturation if its temperature were lowered or if the atmospheric pressure were increased. Both lower temperatures and higher pressures affect the oxygen content of Birch Creek at night.

The dissolved-oxygen-saturation data support other observations of differences in biological activity between the two years of study. Daily ranges of oxygen saturation were greater in 1961 than in 1962. Apparently oxygen production during the day and oxygen utilization during the night were both higher in 1961 than in 1962. The greater range in oxygen saturation in 1961 seems related to increased production and consumption of oxygen in 1961, which indicates that biological activity was greater in 1961 than in 1962.

MAJOR IONS

Water samples for complete analysis were taken at 1500 and 0300 hours during each 24-hour study with the expectation that they would represent maximum

changes undergone by a mass of water of uniform composition reacting mainly to changes in solar radiation. It must be emphasized, however, that samples at 12-hour intervals were not drawn from the same mass of water. Differences between two samples can result from differences in initial composition of water reaching the stream channel, from changes occurring during streamflow, including daily effects, or from combinations of factors. Sample composition also may change during storage (Slack and Fisher, 1965). Comparison between laboratory and field measurements on duplicate samples showed clearly that some properties changed between collection and analysis. Although the effect on conservative solutes is slight by definition, original concentrations of biologically active substances probably changed despite attempts to preserve them.

Two generalizations, can be made from results shown in tables 5 and 6. First, the water was a calcium-magnesium carbonate type with nothing extraordinary about its composition. Second, the concentration of conservative ions such as sodium and chloride increased only about 10 percent between station 5 and the terminal station downstream; thus, evaporation accounted for only 10 percent of the water lost over the same reach.

MINOR ELEMENTS

Most minor elements occur in concentrations less than 100 micrograms (1 mg) per liter in natural waters (Durum and Haffty, 1963). Knowledge of the occurrence of minor elements in water is a prerequisite to understanding geochemical and hydrologic processes such as weathering and denudation. Some minor elements are essential nutrients for living organisms, and these elements may be removed from water by the biota as fast as they are supplied.

Water samples from Birch and Wyman Creeks were analyzed for the 17 minor elements listed in table 7. With few exceptions, minor elements were near the lower limit of detection by the method used. The Wyman Creek sample had greater concentrations of aluminum, iron, manganese, nickel, titanium, and vanadium than the Birch Creek samples. Water of both creeks had generally lower concentrations of minor elements than median values for concentrations in large rivers of North America (Durum and Haffty, 1963). The concentrations of vanadium were somewhat higher in the Wyman Creek sample and in one Birch Creek sample than the median concentrations in large rivers. Cobalt, manganese (Wyman Creek), molybdenum, and zinc were of the same order of magnitude as the median values. Durum and Haffty (1963) did not include data for beryllium, bismuth, cadmium, gallium, or germanium. Concentrations of beryllium, cadmium, and gallium determined in this study are in the lower range of values given by Livingstone (1963).

TABLE 5.—Composition of water samples, in parts per million from daily studies of Birch and Wyman Creeks, Calif., 1961

[Heavy metals in solution at time of analysis; Ca determined from acidified sample]

Station	5	4		3		1		Wyman Creek
Date	5-26	6-3	6-4	6-5	6-6	5-23	5-24	6-6
Time (P.s.t.)	1617	1515	0315	1518	0304	1530	0322	1802
SiO2	22	21	17	21	18	21	21	21
Fe	.01	.00	.01	.00	.00	.00	.00	.34
Ca	76	76	77	74	76	52	65	65
Mg	25	24	24	21	24	23	23	16
Na	13	13	14	14	11	11	11	11
K	3.4	3.3	3.6	3.4	3.5	3.6	3.2	2.9
SO4	93	93	94	93	93	100	94	42
Cl	5.0	4.5	4.5	4.5	5.0	4.5	4.0	2.5
F	.7	.7	.6	.7	.7	.7	.5	.1
NO3	.2	.3	.3	.4	.3	.1	.2	.2
PO4	.07	.02	.69	.00	.15	.04	.05	.09
Al	.1	.0	.0	.1	.1	.1	.0	.1
Mn	.00	.00	.00	.00	.00	.00	.00	.07
Cu	.00	.00	.00	.00	.00	.04	.00	.02
Zn	.0	.0	.3	.0	.0	.0	.0	.0
Sr	.4	.4	.4	.3	.4	.3	.3	.4

TABLE 6.—Composition of water samples, in parts per million, from daily studies of Birch and Wyman Creeks, Calif., 1962

[Samples fixed with chloroform; heavy metals in solution at time of analysis. Ca determined from acidified sample. Where asterisk (*) appears, refer to table 7 for values]

Station	5		3		1			0		Wyman Creek	
Date	7-24	7-25	7-20	7-21	7-14	7-15	7-16	7-9	7-10	8-6	8-7
Time (P.s.t.)	1500	0500	1500	0300	1500	1500	0300	1500	0300	1500	0300
SiO2	21	25	21	20	21	21	21	22	20	23	23
Fe	(*)	(*)	(*)	(*)	.01	.01	.01	(*)	(*)	(*)	.03
Ca	80	*78	77	81	59	57	71	55	70	60	65
Mg	24	25	24	22	26	21	23	26	23	13	13
Na	10	10	11	10	11	11	10	12	16	9.2	8.7
K	2.9	2.8	2.7	2.9	2.9	2.9	2.9	3.2	4.1	2.4	2.4
SO4	105	105	105	104	106	107	104	107	108	46	44
Cl	4.4	3.8	3.9	4.1	4.4	4.2	4.0	5.5	4.2	3.7	3.1
F	.6	.6	.6	.6	.5	.6	.6	.6	.5	.1	.1
NO3	.5	.3	.4	.5	.1	.1	.3	.2	.2	.1	.0
NO2	.02	.03	.03	.02	.03	.02	.03	.04	.03		
PO4	.00	.00	.00	.00	.00	.00	.00	.00	.00	.02	.10
Al	(*)	(*)	(*)	(*)	.1	.1	.0	(*)	(*)	(*)	.1
Mn	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Cu	.00	.00	.00	.00	.01	.01	.01	.02	.00	.04	.04
Zn	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0

* Estimated.

Table 7.—*Concentrations of minor elements, micrograms per liter, in water samples from Birch and Wyman Creeks, Calif., 1962*

[Spectrographic analyses made by W. D. Silvey]

Station	5		3		0		Wyman Creek
Date	7-24	7-25	7-20	7-21	7-9	7-10	8-6
Time (P.s.t.)	1500	0300	1500	0300	1500	0300	1500
Al	13	6.8	22	16	31	16	89
Be	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
Bi	<.50	<.50	<.50	<.50	<.50	<.50	<.50
Cd	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
Cr	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
Co	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
Cu	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
Ga	<10	<10	<10	<10	<10	<10	<10
Ge	<.50	<.50	<.50	<.50	<.50	<.50	<.50
Fe	81	6.0	7.0	5.5	23	16	90
Pb	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5
Mn	<2.5	<2.5	<2.5	<2.5	<2.5	<2.5	22
Mo	≷.50	≷.50	≷.50	≷.50	≷.50	≷.50	<.50
Ni	.70	≷.50	≷.50	≷.50	≷.50	.90	.85
Ti	<1.0	<1.0	<1.0	<1.0	1.4	<1.0	2.6
V	<.50	<.50	<.50	<.50	≷.50	<.50	1.3
Zn	<10	<10	<10	<10	<10	<10	<10

In the Birch Creek samples, aluminum concentration increased downstream. Iron concentration was greater in water taken at station 0 than in that taken at station 3, but the highest concentration from Birch Creek was in the 1500 hours sample from station 5. High iron concentration at station 5 was expected because of an iron-rich seep in the wet meadow, although the low iron value for the 0300 hours sample is difficult to explain. All samples collected during the day at Birch Creek had higher concentrations of aluminum and iron than did the samples collected at night.

Possibly the downstream increase in aluminum and the differences in concentration of aluminum and iron in samples taken at 1500 and 0300 hours resulted from the large daily changes in stream properties. Solubility of aluminum would be highest during the day at downstream stations where pH and water temperatures were highest. Decreased streamflow during the day also may have resulted in greater concentration of fine sediment in the day samples than in the night samples. Particles smaller than 2 mu which passed through the filter pad would add to the concentration of aluminum and iron. The possibility that biological processes were involved in some way in control of iron and aluminum concentrations is suggested by spectrographic analyses of samples of the streambed algae. Iron and aluminum were the most abundant constituents in dried samples of algae from stations 3–5.

DISCUSSION

CONTROLS ON TRAVERTINE FORMATION

Calcium carbonate deposition may result from changes in bulk composition of water, or it may occur in association with living tissues of calcareous algae. Changes in water properties sufficient to cause travertine deposition in Birch Creek result either from inorganic or organic processes. Biological agencies play a double role in the formation of travertine—by removing free CO_2 from solution during photosynthesis, and by direct deposition of $CaCO_3$ crystals within the plant thallus as the result of physiological processes.

Dissolved oxygen concentrations in Birch Creek are inversely related to temperature, an example of inorganic control. In 1961, dissolved oxygen concentrations and percent saturations were higher during daylight hours than they were in 1962, except at station 5. Data from stations 1 and 3 for the two years show this (pl. 1). Higher oxygen concentrations during the day in 1961 as compared with values in 1962 are interpreted to be the result of greater photosynthesis in 1961. Decreased photosynthesis in 1962 may have been due to erosion of the algal bearing travertine prior to the 1962 study. Higher dissolved oxygen concentrations during darkness in 1962 compared with those in 1961 may also be explained by lower respiration demands of a smaller plant and animal population in 1962.

Travertine would be precipitated in Birch Creek in the absence of aquatic life. Barnes (1965) showed that the emerging ground water was supersaturated with calcite and with CO_2 relative to the overlying atmosphere and that calcite supersaturation increased downstream. If inorganic processes were the only controls, turbulent flow and higher water temperatures toward Deep Springs Valley would result in travertine deposition at a slower rate and with a different gross structure than if organic processes were also involved. The system under investigation had organic as well as inorganic controls, although the organic component was diminished at times. It should be emphasized that organisms were not absent in 1962. Although floating and attached algae were much less abundant in 1962, algae and immature insects of several orders were present, even in areas of maximum scour. Thermodynamic analysis of free CO_2 (Barnes, 1965) provided strong proof of biological control of the CO_2 concentration at station 1 in 1961. Plants and animals, in combination with inorganic controls, influenced water properties throughout the stream during both years. Separation of the two is rarely possible because both inorganic and organic controls vary directly with solar radiation.

VARIABILITY

Properties of Birch and Wyman Creeks differed from those of typical humid-region streams in that discharge and solute concentration in Birch and Wyman Creeks decreased with downstream distance, and dissolved oxygen concentration was inversely related to insolation. These creeks are also exceptions to the generalization,

for regions of interior drainage, that the content of dissolved matter tends to increase from source to mouth (Livingstone, 1963). Ground water of virtually uniform composition emerged above station 5 with a bicarbonate ion concentration between 260 and 270 ppm and carbonate ion concentration about 1.0–1.5 ppm. Calcite precipitation and loss of CO_2 to photosynthesis and to the air resulted in decreased HCO_3^- concentrations and increased CO_3^{-2} concentrations as the water passed downstream. These changes were accompanied by a general downstream increase in the range of daily variation.

Alteration of stream water during flow may be considered either as spatial changes undergone by a volume of water in transit or as temporal changes in the properties of water passing a point in space. Water moving past a point on the bank of a spring stream like Birch Creek exhibits daily patterns of variation, as this study shows. One intuitively relates these observations to a model stream which receives all its flow from a point source of uniform discharge and composition. Under such ideal conditions, departures from initial composition (for example, daily fluctuations measured at a single station) would reflect the composition of the water at the source and the type, magnitude, and duration of modifying influences acting upon the water. If the modifying influences were uniform or exhibited gradual predictable changes, water properties would change uniformly downstream, the greatest departures occurring farthest from the source. In general, the expected downstream increase in magnitude of daily fluctuations in Birch Creek was confirmed during both years if comparisons of measurements made on different days at different stations are valid. When time-series data from individual stations are examined, the ideal model clearly does not apply in detail. The observed departures from predicted conditions may provide additional insight into the environmental dynamics of these streams.

The 1961 study of Birch Creek disclosed hour-to-hour variations in several properties, notably pH, carbonate species, and dissolved oxygen, in addition to the spatial and daily patterns of change. Variability was generally greatest during the day at stations between the uppermost and the lowermost stations. At times the fluctuation in composition had an apparent periodicity which was most evident in pH and dissolved-carbonate-species curves for stations 3 and 4 in 1961 (pl. 1). The periodicity was confirmed during the second field season, in spite of radical differences in flow and bed conditions. The station on Wyman Creek also showed the variability in water composition.

The pattern of dissolved oxygen variation in natural waters which is considered to be typical shows maximum concentration during the afternoon (the result of excess oxygen production over consumption) and minimum concentration just before dawn (the result of oxygen consumption during respiration by aquatic organisms). Conversely, carbon dioxide is removed from solution by photosynthesis during the day and released both day and night by respiration. Thus, the daily fluctuation in free CO_2 concentration is expected to be the mirror image of the pattern for dissolved oxygen concentration (Odum, 1956). In many studies the typical daily pattern for dissolved-oxygen concentration has not been observed, as was shown in a review by Gunnerson (1964).

Dissolved-oxygen and free CO_2 concentrations at station 5 were remarkably uniform because of the influx of ground water from seeps. Below station 5 both dissolved-oxygen and free CO_2 concentrations exhibited the same diurnal pattern of variations: minimum concentrations occurred during the afternoon and maximum concentrations occurred at night.

The dissolved-oxygen values showed much greater hour-to-hour uniformity than the free CO_2 values (pl. 1). A similar observation was reported for the much deeper outflow from Silver Springs, Fla. (Odum, 1957). It was suggested that in Silver Springs the smoother dissolved-oxygen curve relative to the free CO_2 curve might result from the fact that bubbles of oxygen rising from plants before being dissolved help to distribute the oxygen uniformly. The uptake of carbon dioxide occurs only at the plant surfaces, thus forming local stratification of free CO_2. It is unlikely that this explanation can be used to account for the differences in variability of dissolved-oxygen and of free CO_2 concentrations in the shallow turbulent water of Birch Creek. Barnes (1965) considered the variability of free CO_2 and related stream properties observed at stations 4 and 3 in 1961 to be reflections of instability in a zone of transition between ground-water control (at the source) and atmospheric control (identified at station 1).

Heterogeneity of water composition in Birch and Wyman Creeks may result from many factors. In his discussion of the periodicity in pH and carbonate-species data, Barnes (1965) suggested that pulses in carbonate precipitation may possibly result from cyclic metabolism rates of the biota. Unsteady channel flow is another possibility. Heterogeneity could result from sudden release of water temporarily impounded along margins or in backwaters; masses of water, if detained in one of the numerous algal-filled shallows of Birch Creek, could acquire pH, HCO_3^- concentration, dissolved gas, and temperature values quite different from those of the

adjacent freely moving water. When the modified wa-
ter rejoined the main flow, it would slowly lose its iden-
tity. A similar argument was advanced to explain
short-term compositional variations which were ob-
served downstream from a large chemostatic and ther-
mostatic spring (Odum, 1957).

Compositional fluctuations may also be related to
pulses in stage, velocity, and discharge which Dement'ev
(1962) described; the pulses he described had periods of
1–3 to 40–50 minutes. Maximum effects were observed
in small mountain streams where the pulse magnitude
increased with current speed and with bed roughness.
This may explain the more frequent occurrence of
short-term variations in composition at stations 3–5 on
Birch Creek, where both current speed and bed rough-
ness were maximal for the stream. Gusty winds blow-
ing up the canyon during the day may also have con-
tributed to unsteady flow in this very shallow stream.
It is significant that abrupt hour-to-hour changes in
composition were most pronounced during daylight,
when conditions were most favorable for organic and
inorganic activity affecting water composition.

The data do not warrant further speculation. More
detailed measurements, preferably continuous record-
ings, are required to identify the causes for short-term
variations in composition in these mountain streams.
The present data, although taken within a few minutes
and a few feet of one another, are not adequate for this
purpose.

A final type of variability noted during this study was
that of channel morphology in Birch Creek. Riffles of
cemented willow litter were apparently short lived, and
even massive deposits of indurated travertine were de-
stroyed from time to time by high flows. The greatest
change was the transition from a completely cemented
bed in 1961 to a completely unconsolidated bed in 1962.
Some effects of this change on water composition have
been discussed, but other implications are equally im-
portant. For example, condition of the channel must
affect the loss or gain of ground water, which may, in
turn, influence stream composition, water temperature,
and the biological community. Nothing is known of
these effects, although losses of organisms undoubtedly
are high following scour of the channel. Replenish-
ment of a decimated population may be very slow where
permanent streams are widely spaced and discontinuous.
During this investigation, downstream drift of or-
ganisms from unaffected habitats may have contributed
to repopulation of barren areas as described by Waters
(1964).

REFERENCES CITED

Barnes, Ivan, 1963, Field measurement of alkalinity and pH:
U.S. Geol. Survey Water-Supply Paper 1535–H, H1–H17.
—— 1965, Geochemistry of Birch Creek, Inyo County, Cali-

fornia, a travertine depositing creek in an arid climate:
Geochim. et Cosmochim. Acta, v. 29, no. 2, p. 85–112.
Blum, J. L., 1960, Algal populations in flowing waters, in The
ecology of algae: Pymatuning Lab. Field Biol., Spec. Pub.
2, p. 11–21.
Dement'ev, V. V., 1962, Investigations of pulsation of velocities
of flow of mountain streams and of its effect on the accuracy
of discharge measurements: Soviet Hydrology, Selected
Papers, no. 6, p. 588–623.
Durum, W. H., and Haffty, Joseph, 1963, Implications of the
minor element content of some major streams of the world:
Geochim. et Cosmochim. Acta, v. 27, no. 1, p. 1–11.
Elmore, H. L., and Hayes, T. W, 1960, Solubility of atmospheric
oxygen in water: Amer. Soc. Civil Engineers Proc., Sani-
tary Eng. Div. Jour., v. 86, no. SA 4, July 1960, p. 41–53.
Fritsch, F. E., 1945, The structure and reproduction of the
algae, v. II: London, Cambridge Univ. Press, 939 p.
—— 1949, The lime-encrusted Phormidium-community of
British streams: Internat. Ver. Theoret., und angew.
Limnol. Verh., v. 10, p. 141–144.
Gregory, J. W., 1911, Constructive waterfalls: Scottish Geog.
Mag., v. 27, no. 10, p. 537–546.
Gunnerson, C. G., 1964, Diurnal and random variations of dis-
solved oxygen in surface waters: Internat. Ver. Theoret.
und angew. Limnol. Verh. v. 15, p. 307–321.
Howe, M. A., 1931, The geologic importance of the lime-secreting
algae: U.S. Geol. Survey Prof. Paper 170–E, p. 57–64 [1932].
Iwasaki, Iwaji, Utsumi, Sartori, and Ozawa, Takejiro, 1952,
New colorimetric determination of chloride using mercuric
thiocyanate and ferric ion: Chem. Soc. Japan Bull., v. 25,
no. 3, p. 226.
Johnston, John, and Williamson, E. D., 1916, The role of in-
organic agencies in the deposition of calcium carbonate:
Jour. Geology, v. 24, no. 8, p. 729–750.
Jones, B. F., 1965, The hydrology and minerology of Deep
Springs Lake, Inyo County, California: U.S. Geol. Survey
Prof. Paper 502–A, p. A1–A56 [1966].
Kesseli, J. E., and Beaty, C. B., 1959, Desert flood conditions in
the White Mountains of California and Nevada: U.S. Army,
Quartermaster Research and Eng. Center, Environmental
Protection Research Div. Tech. Rept. EP–108, 108 p., 1 pl.
Lewin, J. C., 1962, Calcification, in Lewin, R. A., ed., Physiology
and biochemistry of algae: New York, Academic Press, p.
457–465.
Linsley, R. K., Jr., Kohler, M. A., and Paulhaus, J. L. H., 1949,
Applied hydrology: New York, McGraw-Hill Book Co.,
689 p.
Livingstone, D. A., 1963, Chemical composition of rivers and
lakes: U.S. Geol. Survey Prof. Paper 440–G, 64 p.
Lustig, L. K., 1965, Clastic sedimentation in Deep Springs
Valley, California: U.S. Geol. Survey Prof. Paper 352–F, p.
131–192.
Macfayden, W. A., 1928, On the deposition of calcareous tufa in a
mountain stream at Binn, Canton Valais, Switzerland: Geol.
Mag., v. 65, no. 1, p. 1–5.
Minckley, W. L., 1963, The ecology of a spring stream Doe Run,
Meade County, Kentucky: Wildlife Mon., no. 11, p. 1–124.
Nelson, C. A., 1963, Preliminary geologic map of the Blanco
Mountain quadrangle, Inyo and Mono Counties, California:
U.S. Geol. Survey Mineral Inv. Field Studies Map MF–256.
Odum, H. T., 1956, Primary production in flowing waters: Lim-
nology and Oceanography, v. 1, no. 2, p. 102–117.
—— 1957, Trophic structure and productivity of Silver
Springs, Florida: Ecological Mon., v. 27, p. 55–112.

Pollock, J. B., 1918, Blue-green algae as agents in the deposition of marl in Michigan Lakes: Mich. Acad. Sci., 20th Rept., p. 247-260 [1919].

Rainwater, F. H., and Thatcher, L. L., 1960, Methods for collection and analysis of water samples: U.S. Geol. Survey Water-Supply Paper 1454, 301 p.

Revelle, R. R. D., and Fairbridge, R. W., 1957, Carbonates and carbon dioxide, chap. 10 of Hedgpeth, J. W., ed., Treatise on marine ecology and paleoecology: Geol. Soc. America Mem. 67, p. 239-296.

Roddy, H. J., 1915, Concretions in streams formed by the agency of blue-green algae and related plants: Am. Philos. Soc. Proc., v. 54, no. 218, p. 246-258.

Silvey, W. D. and Brennan, Robert, 1962, Concentration method for the spectrochemical determination of seventeen minor elements in natural water: Anal. Chemistry, v. 34, no. 7, p. 784-786.

Slack, K. V. and Fisher, D. W., 1965, Light-dependent quality changes in stored water samples: U.S. Geol. Survey Prof. Paper 525-C, p. C190-C192.

Twenhofel, W. H., 1950, Principles of sedimentation: 2d ed., New York, McGraw-Hill Book Co., 673 p.

U.S. Weather Bureau, 1961, 1962, Climatological data, California: Asheville, N.C., v. 65, nos. 5 and 6; v. 66, nos. 5-8.

Waters, T. F., 1964, Recolonization of denuded stream bottom areas by drift: Am. Fisheries Soc. Trans., v. 93, no. 3, p. 311-315.

Weed, W. H., 1889, Formation of travertine and siliceous sinter by the vegetation of hot springs: U.S. Geol. Survey 9th Ann. Rept., p. 619-676.

Yount, J. L., 1956, Factors that control species numbers in Silver Springs, Florida: Limnology and Oceanography, v. 1, no. 4, p. 286-295.

O