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Limnological Studies and Remote Sensing of the Upper Truckee River Sediment Plume in Lake Tahoe, California-Nevada

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Five studies of the Upper Truckee River sediment plume in Lake Tahoe were conducted in California-Nevada using aerial photography and simultaneous measurements in the lake. The aerial and "water truth" studies covered a range of river discharge conditions during the snowmelt-runoff period in the spring of 1971. Color and multispectral aerial photography allowed delineation of the extent and relative density of four to five units within each plume. Simple correlation coefficients are high between these units and measures of suspended sediment, dissolved inorganic carbon, and light penetration, as well as measures of primary productivity and heterotrophic activity. Correlations are inconsistent between the above variables and nutrients (N-NO_3, P-PO_4, and Fe) apparently due to biological utilization of the latter in Tahoe's nutrient-poor environment. Two studies were conducted in the morning and afternoon of a single day; the plume's eastward shift during the day was recorded photographically and with limnological measurements. High correlations between sediment plumes and biological productivity coupled with evidence that silt particles and associated nutrients stimulate bacterial growth indicate that sediment plumes are accelerating the eutrophication of Lake Tahoe.

I. Introduction

Accelerated eutrophication of Lake Tahoe, an oligotrophic subalpine lake, has been evident from casual observation of algal growth in shallow water and measured increases in primary productivity and algal biomass of phytoplankton (free-floating algae) as well as periphyton biomass (attached algae) (Goldman and Armstrong, 1969; Goldman, 1970; and Goldman et al., 1972). These authors also investigated tributary streams, the major source of nutrient enrichment, and demonstrated stimulatory effects of stream water on growth of the natural phytoplankton population in Tahoe water. In addition, *in situ* sampling of transects toward (the mouth of) the Upper Truckee River, the major tributary, indicated increases in both heterotrophic (bacterial) activity and primary productivity as the stream mouth was approached (Paerl and Goldman, 1972a). These results, coupled with evidence of recently doubled sediment contribution to the Upper Truckee River from man-made disturbances on its watershed (Calif. Dept. of Conservation, 1969), point strongly to siltation as an increasingly important and continuing cause of lake enrichment. (This is particularly true now that treated sewage effluent is exported from most of the lake basin and is considered less of a threat to water quality than it was in the past.)

The influence of major tributaries on lakes and rivers has long been studied (Hutchinson, 1957, p. 295). Water masses peculiar to an inflowing river or stream have been traced and identified in the receiving water body through measurement of various parameters. Movement of the Rhine River through Lake Constance (Numann, 1938), the Rhone through Lake Geneva (Dussart, 1948) and the Colorado through Lake Mead (Anderson and Pritchard, 1951) are all cases in point. The biological influence of tributaries on lake fertility has been evaluated by bioassay in a number of Alaskan and Californian lakes (Goldman, 1964). Temperature, oxygen, light transmission, dyes, sediment load, conductivity, and chemical and biological changes have all been utilized to some extent. Few studies have, however, coupled the use of limnological field methods with high resolution aerial photography to provide an overall view of the process. In this study, simultaneous photography and water sampling have provided a nearly instantaneous measure of variation in biological productivity and physical changes in the lake under the influence of its major tributary.

A joint study by Ames Research Center (NASA) and the University of California at Davis was begun in early 1971 to document the influence of the Upper Truckee River sediment plume on eutrophication of Lake Tahoe. The study area is shown in Fig. 1. The major objective was to determine if high-resolution aerial photography could be used to correlate location of the plume with biological, physical, and chemical conditions measured in the water mass and indicate the value of photography in defining plume limits. Another objective was to investigate the relationship between siltation and the process of eutrophication. Lake Tahoe is particularly appropriate for this study because the water is extremely clear and the plume varies seasonally in volume and intensity. Spring snowmelt water entering the Upper Truckee River from the highly urbanized South Lake Tahoe Valley area produces the most significant sediment plumes observed in the lake.

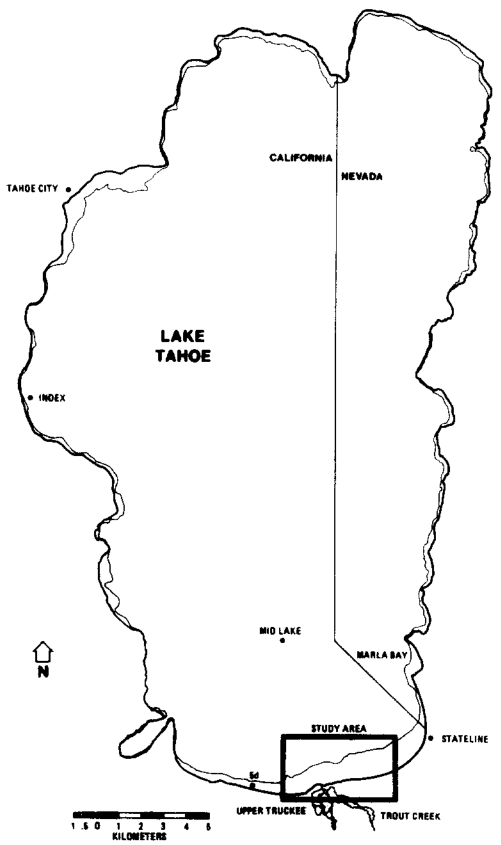


FIG. 1. Lake Tahoe, California-Nevada. The rectangle encloses the study area. Stations Index, midlake and 5d, not shown on Figs. 3–7 are shown here. A thin line around the lake periphery indicates 6-m depth.

II. Methods

A. Sampling-Time Selection

Observation of changing meteorological conditions in northern California-Nevada and onsite reconnaissance was used to select sampling dates during the 1971 spring runoff. Sampling was scheduled to include a variety of runoff stages, encompassing low and peak flows. Past stream-flow records for the Upper Truckee River were combined with meteorological data, primarily air temperatures, to predict runoff development. It was also necessary to have favorable conditions for aerial photography over water: clear skies, low windspeed (< 10 kt), and moderate sun angle (30–50° above the horizon). The latter was accomplished by conducting the photography during the early morning or late afternoon. Lack of favorable conditions prevented sampling during May.

B. Field Methods

While aerial photographs were being taken, samples for chemical analysis, biological activity, and physical characteristics of the plume area were collected along transects radiating from the Upper Truckee River mouth. Shallow water samples were taken near the bottom, deep water samples at 20 m. A fast boat usually made collection possible during a 3-h period. Station location was achieved by sighting onshore landmarks and prominent bottom features. Samples were transported in darkened ice chests to the laboratory. Additionally, on-site measurements at the twenty stations usually included light transmission (G. M.® photometer), temperature (Martek® thermistor), Secchi disc measurements, and field notes on visual conditions of the water.

Primary (algal) productivity samples were transferred to 125 ml Pyrex® bottles, injected with ^{14}C-bicarbonate, and incubated *in situ* for 4 h at 2-m depth from a lakeside pier (Goldman, 1963; Goldman and Carter, 1965). Morning samples were incubated the same afternoon. The June 20 afternoon samples were held overnight in the dark at lake surface temperature and incubated the following morning.

Heterotrophic (bacterial) activity samples were transferred in parallel to 125 ml opaque (Pyrex® bottles). Heterotrophic assimilation of 2-^{14}C acetate was measured by adding a trace amount (10 ng acetate $\cdot$ l^{-1} of carbon-14 labeled substrate to each water sample. Incubation was done in a darkened incubator with rotator. Incubation temperatures were held close to sampling temperatures. Assimilation rates were compared throughout the sampling period. In earlier work (Paerl and Goldman, 1972a), assimilation of acetate was shown to be largely due to bacteria in Lake Tahoe and acetate concentrations in the lake (derived from both gas chromatographic analyses and kinetic plots) varied from 1 to 10 μg acetate $\cdot$ l^{-1}. (Microautoradiography was employed in the earlier study to demonstrate bacterial uptake and absence of algal uptake of ^{14}C acetate at the substrate concentration used in experiments reported here.)

Incubation of heterogenous samples taken at depths ranging from 0.5–20.0 m and differing environmental surroundings (light, temperature, nutrients, etc.) do not give absolute *in situ* values of primary productivity and heterotrophic activity. The values are an index of the ability of different phytoplankton and bacterial populations to respond to stimuli under similar, measurable conditions. Both sets of samples were filtered at low vacuum on 25-mm, 0.45-μm filters (HA Millipore®) immediately after incubation. Air-dried filters were counted with a Geiger-Muller ultrathin window counter and scaler (Nuclear-Chicago®), calibrated with gas phase (Goldman, 1968), or a Beckman® LS-100 liquid-scintillation counting system.

The remainder of the water sample was divided into smaller containers for determination of dissolved inorganic carbon (DIC), sediment content, water chemistry, and phytoplankton identification and enumeration. Dissolved inorganic carbon, composed mainly of HCO_3^-, was determined immediately by infrared analysis using $NaHCO_3$ standards (Armstrong et al., 1971). Water chemistry samples were immediately analyzed or preserved by freezing. Phosphate, nitrate, and iron analyses were done according to procedures for microgram quantities (Strickland and Parsons, 1968), with modifications by Fujita (1971, unpublished).

Phytoplankton samples preserved in Lugol's solution were filtered (0.45 μm) and the filters oil cleared. Phytoplankton were counted by species from a filter area large enough to allow less than 10% error in total count. A Wild® inverted microscope equipped with an image-splitting eyepiece for cell-volume (biomass) calculations was used. Primary productivity, phytoplankton numbers, biomass, and correlation coefficients were computed on a Burroughs® 6700. Suspended sediment samples were filtered through 47-mm, 0.8-μm filters (AA Millipore®) and dried for 24 h at 110°C. Filter weight corrected for an average loss on drying was subtracted from the weight of the filter with its retained sediment.

C. Photographic Coverage

The Upper Truckee River sediment plume was photographed at each sampling time to yield overlapping coverage about 20 km^2 at a scale of 1:20,000. Each photographic mission used a Kargl K3B camera of 225 × 225 mm format and either a 305 mm or 210 mm focal length lens. Kodak® 2448 color film was developed to a positive transparency. On one mission, multispectral and color photographs were taken simultaneously to evaluate application of multispectral photography to sediment-plume study. An International Imaging Systems MK 1 multispectral camera recorded four wavelength band images on different squares of the same 225 × 225 mm negative. The scale was 1:42,000. Wratten® 25, 57a, and 47b filters were used on lenses photographing red, green, and blue wavelengths, respectively, along with special infrared blocking filters. Only a Wratten® 88a filter was used on the lens photographing near infrared. Multispectral film was developed to a negative and positive transparencies were used for sediment–plume study.

Photographic analysis involved converting photographs into line drawings and determining the extent of various units of differing visual contrast within the plume. Silt-laden river water entering the lake from the Upper Truckee River contrasts strongly with clear lake water and the shallow shelf bottom. As the river water intrudes further into the lake, various water masses develop which change in position and visual contrast with time. Their boundaries can usually be delineated with little difficulty. They can be mapped as discrete areal units and assigned density values representing degrees of contrast. Beyond the shallow shelf (6 m), the bottom slopes precipitously. Contrasts are still visible but estimated density values are less accurate. Units beyond the shelf are often extensions of near-shore plume units which allow successful extrapolation. Four or five values of contrast density were assigned in each plume study. Heavily silt-laden river water was given a value of "1." Higher numbers were assigned as the visual contrast against the shelf bottom decreased. Contrast values are valid only for relative comparisons at a given time and are only generally similar for different sampling dates. In one case it was necessary to assign the values "1a" and "1b" because two areal units had similar values of contrast but differed in color. Line drawings were superimposed on a modified USC and GS chart 5001 showing sampling stations, shoreline, and the offshore shelf margin.

III. Results

A. Development of the Sediment Plume

Four days were selected for study: March 29, April 12, June 7, and June 20. These represented a variety of snowmelt-runoff stages during 1971. On June 20, photographs and water samples were taken in both early morning and late afternoon with photographic coverage by both color and multispectral cameras in the morning. Daily streamflow data for the Upper Truckee River and Trout Creek were supplied by the Water Resources Division of the Geological Survey in Carson City [Fig. 2(a)]. The March 29 and April 12 studies occurred during early stages of snowpack melting while those of June 7 and June 20 bracket peak melt runoff. Also shown are daily maximum and minimum air temperatures at Tahoe Valley airport [Fig. 2(b)] and precipitation data taken at Tahoe City [Fig. 2(c,d)]. Tahoe City is not in the Upper Truckee River watershed but it is the only precipitation station in the Tahoe Basin.

Figure 2(a) shows that from October 1970 to late March 1971, runoff is generally very low (daily average about 1 $m^3 \cdot sec^{-1}$). However, some restricted periods of high runoff do occur. Runoff peaks on November 25, January 17, and March 26 were due to heavy rain and/or snow that melted soon after falling.

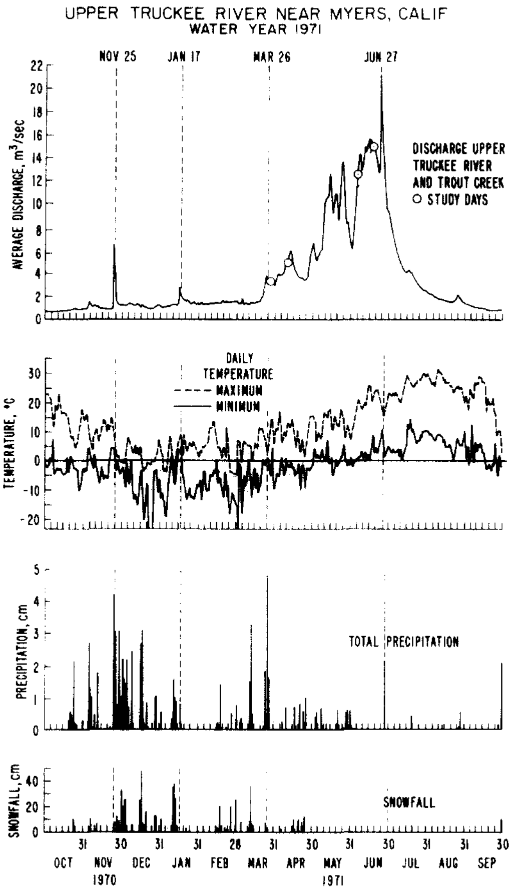


FIG. 2. Seasonal variation in stream flow (a), maximum and minimum air temperatures (b), precipitation (c), and snowfall (d) for the period Oct. 1970 to Sept. 1971. Streamflow data are for the sum of the Upper Truckee River near Meyers and Trout Creek near Tahoe Valley, air temperature data is from Tahoe Valley airport, and precipitation and snowfall data are from Tahoe City.

Figure 2(c,d) shows total precipitation at Tahoe City was high on November 25 and March 26 but snowfall was low compared to other days. This implies conditions of alternating rain and snow with most of the precipitation as rain. On January 17, a total of 0.8 cm precipitation fell despite no record of snowfall. Thus, isolated peaks in runoff during low flow periods from October 1970 to late March 1971 were produced by heavy rains and rapidly melting snow. The March 29 study was shortly after the day of maximum yearly precipitation at Tahoe City. On March 26, the precipitation consisted mostly of rain. It is likely that this rain had a pronounced effect on plume formation three days later.

Spring melting of the Tahoe Basin snowpack produced large runoff in the Upper Truckee River and Trout Creek from late March to late June [Fig. 2(a)]. Diurnal fluctuations in runoff rate occurred due to insolation and warmer daytime air temperatures followed by cooler night-air temperatures. Figure 2(b) shows that when daily minimum temperatures consistently exceeded freezing, runoff became large, and flow variations followed daily maximum temperature fluctuations. When daily maximum temperatures exceeded 15°C, runoff neared its maximum. A major cooling trend in late May reduced runoff more than 50% although daily minimum temperatures did not drop.

There appears to be increasing sediment plume development associated with increasing runoff of melting snowpack. This would be expected due to increased displacement of lake water by turbid river water. Figures 3–7 show maps of each sediment plume outline and various units of differing visual contrast densities within the plumes. The March 29 and April 12 plumes are confined to the lakeshore east of the river mouth and extend northerly to just beyond the shallow-shelf edge. Both plumes of June 20, near maximum runoff, extended far into the lake ($>$ 3 km) and along the eastern shore as far as Marla Bay, 8 km from the river mouth (Fig. 1). We have no explanation for the fact that the June 7 plume occurred during high runoff but had the smallest total outlined area. It contained the largest extent of highly contrasted (density values 1 and 2) areal units of all morning plumes. Total mapped areas of morning plumes are not a strong function of runoff even excluding the June 7 plume: a 40% increase in plume area occurred from March 29 to June 20 while runoff increased 400%. Multispectral photographs of the June 20 morning plume (Fig. 8) show much greater plume area, especially to the north, than color photographs and indicate observational difficulties with color film.

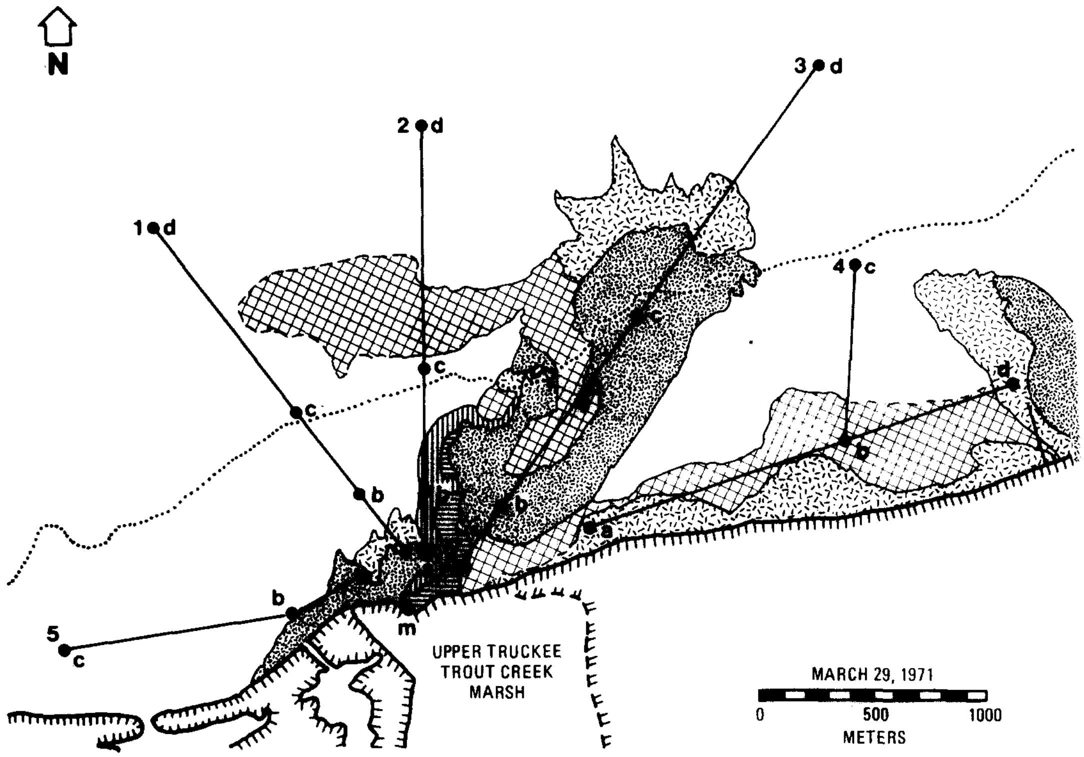
Figure 8 also shows differing responses to the plume among the spectral bands. Blue band response delineates the plume envelope well in both shallow and deep water but loses detail in dense plume areas; the effect appears to be a reduction of upwelling light by scattering or absorption or both. Against the bright, shallow shelf the green band shows less reduction of upwelling light than the blue and provides some interior plume structure. In deep water, denser plume areas appear bright in green light against a dark background due to reflection from suspended sediment. Reflection predominates in very dense plume areas in the red band and provides more internal structure, but in somewhat less dense plume areas sediment reduces upwelling red light creating a dark area against the shelf. Thus, there is a gradation between reflection and absorption which is dependent upon sediment concentration. No infrared light derives from either clear or sedimented areas due to a large attenuation coefficient in water for this band and an apparent lack of significant amounts of sediment at the surface.

B. Relationship Between Aerial Photographic Interpretations and Aquatic Measurements

Sediment-plume density maps based on relative visual contrasts of adjacent water masses are in good agreement with water-property measurements and field observations as detailed below.

1. Suspended Sediment

Visually dense plume units near the river mouth contain the most suspended sediment whereas less dense, more extensive units contain less sediment (Figs. 3–7). Sediment from all plumes consists primarily of silt-size mineral grains of feldspar, mica, quartz, and hornblende in order of decreasing abundance according to x-ray diffraction and microscopic analyses. These minerals comprise a large por-

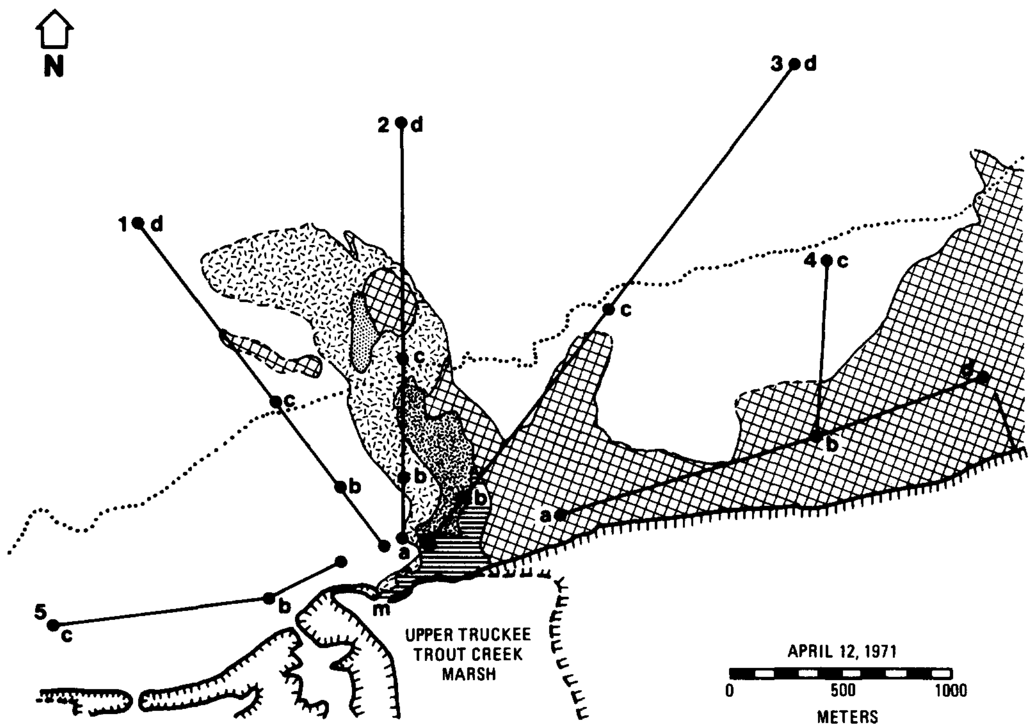


STATION	SUSPENDED SEDIMENT	DIC	PRIMARY PRODUCTIVITY
UT MOUTH	7.5	5.5	30
1A	0.8	10.8	44
1B	0.4	11.2	3
1C	0.3	11.0	18
1D	0.5	10.5	30
2A	0.6	10.0	22
2B	2.5	9.6	22
2C	0.6	9.8	20
2D	0.1	9.9	19
3A	8.8	7.5	42
3B	5.9	7.4	24
3C	33.5	9.7	42
3D	0.1	9.8	29
4A	17.5	9.8	100
4B	4.2	8.0	47
4C	0.6	9.5	27
4D	–	–	–
5A	–	–	–
5B	–	–	–
5C	–	–	–
5D	0.3	9.7	29
Mid Lake	0.2	10.2	16
Index	0.3	9.6	8

VISUAL PLUME DENSITY

m	RIVER MOUTH	▤	1 a/b (MOST DENSE)
●	SAMPLING STATION	▒	2
······	SHELF MARGIN	░	3
⊓⊓⊓	SHORE LINE	▦	4 (LEAST DENSE)

FIG. 3. Transect area at South Lake Tahoe showing the sediment plume for March 29, 1971. Values for suspended sediment are in $mg \cdot l^{-1}$, DIC in $mgC \cdot l^{-1}$, heterotrophic activity in μg acetate $\cdot m^{-3} \cdot h^{-1}$ of assimilation and primary productivity $\times 10^{-2}$ in mg C $\cdot m^{-3} \cdot h^{-1}$ of incubation. The same units also apply to Fig. 4–7.



STATION	SUSPENDED SEDIMENT	DIC	HETEROTROPHIC ACTIVITY	PRIMARY PRODUCTIVITY
UT MOUTH	9.1	5.5	150.6	24
1A	0.5	10.8	5.7	<1
1B	0.4	11.2	5.3	12
1C	0.4	11.0	5.5	15
1D	0.5	10.5	2.2	12
2A	0.4	10.0	21.2	6
2B	0.3	9.6	7.5	2
2C	0.4	9.8	8.6	11
2D	0.3	9.9	3.3	14
3A	7.4	7.5	169.9	61
3B	4.3	7.4	152.6	20
3C	0.3	9.7	4.4	9
3D	0.6	10.1	4.8	25
4A	2.3	9.8	50.4	16
4B	5.8	8.0	48.2	19
4C	0.3	9.5	5.3	16
4D	1.6	9.5	95.5	22
5A	1.5	10.6	5.9	6
5B	0.7	9.9	8.2	6
5C	0.6	9.9	4.4	5
5D	0.3	10.0	3.5	9
Mid Lake	0.1	10.2	–	16

VISUAL PLUME DENSITY

m	RIVER MOUTH		1 (MOST DENSE)
●	SAMPLING STATION		2
·······	SHELF MARGIN		3
	SHORE LINE		4
			5 (LEAST DENSE)

FIG. 4. Transect area at South Lake Tahoe showing the sediment plume for April 12, 1971.

tion of bottom sediments in this area of the lake (Court et al., 1972). Combustible material (organic matter) is generally present in amounts less than 20% by weight. Inspection of filtered sediment residues revealed that samples from dense plume units near the mouth are generally coarser grained than those from plume units of lesser visual density. This indicates that dispersion of sediment from the river mouth is, in part, a function of grain size and implies that photographically defined units are units of differing suspended sediment size as well as quantity.

2. Water Chemistry

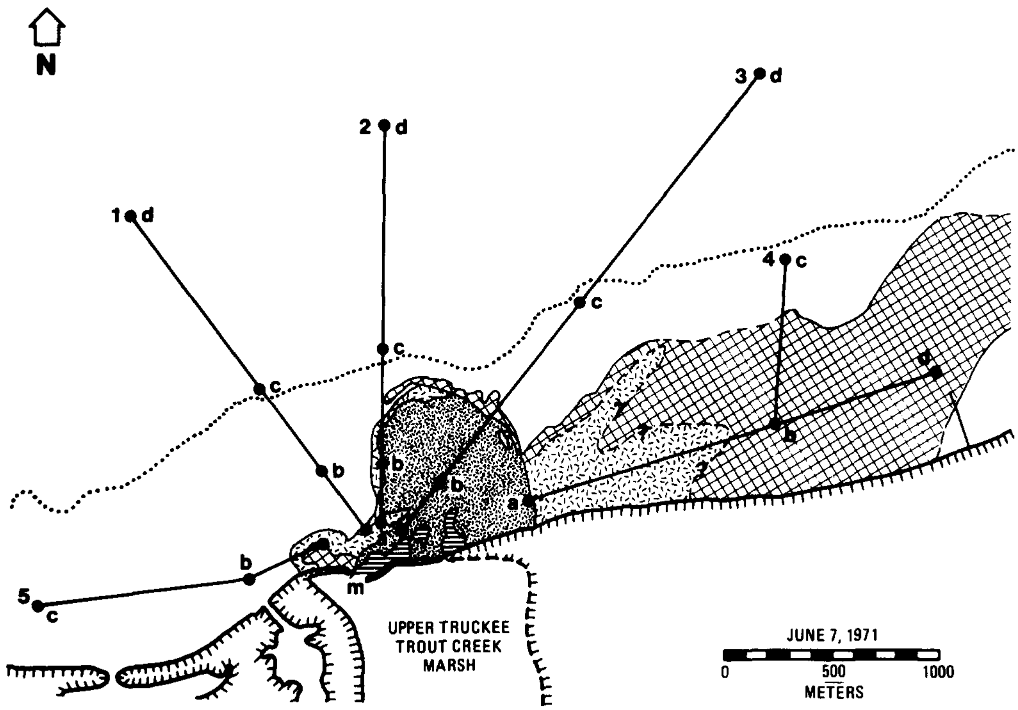
(a) *Dissolved Inorganic Carbon* (*DIC*). In all plume transects, except that of March 29, there appeared to be a strong relationship among increasing plume density, increasing suspended sediment, and decreasing DIC; Table 1 shows correlations at confidence levels above 99.9%. The river mouth always had the lowest DIC. Values increased in irregular fashion away from the mouth in a way highly dependent upon plume configuration. At stations where isolated lenses of turbid water occurred, DIC was lower. This measurement appears to have promise as a water mass marker where differences between river (3–5 $mgC \cdot l^{-1}$) and lake (8–10 $mgC \cdot l^{-1}$) are great enough.

(b) *Nutrients*. Three of the biologically more important nutrients ($N - NO_3^{-1}$, $P - PO_4^{-3}$, and Fe) were sampled and analyzed from all studies except the first two, which did not include iron analyses. Results show that inflowing river water is consistently nutrient enriched relative to midlake and Index station waters; Fe by a factor of 25, $N - NO_3^{-1}$ and $P - PO_4^{-3}$ by factors of 10. There is a spotty relationship between nutrients and either plume density values, suspended sediment, or DIC. Table 1 shows nutrients correlate well with these parameters for the first two studies but only moderately or poorly for other studies. Sample sites west of the plumes consistently had nutrient contents similar to midlake. Samples from regions directly influenced by inflowing river water had nutrient contents intermediate between river mouth and midlake waters. Iron and phosphate concentrations at almost all stations north and east of the river mouth increased significantly from morning to afternoon on June 20. Nitrate concentration increased to a lesser extent. The greatest increases occurred at station 4b, from 18 to 40 ppb iron, 17 to 32 ppb phosphate and 6 to 10 ppb nitrate. This nutrient change paralleled photographically observed eastward movement of the plume.

3. Temperature and Light Measurements

Temperature readings were not taken during March, but during all other morning samplings river mouth temperatures were lower than any lake station. They increased during the season from 3.0°C on April 12 to 8.8°C on June 20 while surface temperatures in clear lake water increased from 5–6°C to 10–12°C. Plume-area surface temperatures directly northeast of the river mouth were always intermediate between those of the mouth and clear water. Vertical temperature gradients in this area indicate that simple density gradient flow occurred. Dense plume units farther from the river mouth had near surface temperatures approximately 1°C higher than clear water, suggesting that solar heating of suspended sediment particles was responsible, in part, for water mass warming. Temperatures in less dense plume units along the shore east of the river mouth were consistently 2–3°C higher than those in similarly shallow clear water to the west. This is consistent with a solar heating mechanism. Such warming created a double valued function of temperature vs. other parameters and precluded good simple correlations. Table 1 shows no consistent temperature correlation with plume density, suspended sediment, or DIC for morning plumes.

The temperature of river mouth water reached 15.5°C during the afternoon of June 20, considerably higher than the morning (8.8°C) and higher than any lake station at the time of sampling (12–15°C). Again stations to the northeast had temperatures intermediate between the river mouth and clear water. Although some vertical mixing of river and lake waters occurred, vertical temperature gradients indicate that river water intrusion took place primarily by surface flow over cooler, more dense lake waters. Surface temperatures in tenuous plume units along the eastern shore and beyond the shelf to the north were higher than temperatures in plume units nearer the mouth. The former approximate the mouth tempera-



STATION	SUSPENDED SEDIMENT	DIC	HETEROTROPHIC ACTIVITY	PRIMARY PRODUCTIVITY
UT MOUTH	14.7	2.7	572.4	67
1A	1.1	9.2	86.6	44
1B	0.2	9.6	9.8	44
1C	0.2	9.6	10.8	15
1D	0.7	9.7	13.8	19
2A	0.3	7.7	174.1	44
2B	0.2	9.3	11.8	33
2C	0.3	9.7	12.9	33
2D	0.2	9.4	5.4	6
3A	6.2	5.5	327.7	54
3B	0.8	8.0	241.7	30
3C	0.6	9.4	22.6	36
3D	0.2	9.6	10.8	36
4A	1.6	6.4	324.4	68
4B	1.0	7.7	148.4	42
4C	0.4	9.3	9.7	27
4D	0.7	8.4	347.0	55
5A	0.6	9.4	50.2	57
5B	0.5	10.5	18.2	6
5C	0.4	10.2	24.7	42
5D	0.2	10.1	7.9	36
Mid Lake	0.6	10.0	4.7	26

VISUAL PLUME DENSITY

m RIVER MOUTH — 1 (MOST DENSE)
● SAMPLING STATION — 2
...... SHELF MARGIN — 3
SHORE LINE — 4 (LEAST DENSE)

FIG. 5. Transect area at South Lake Tahoe showing the sediment plume for June 7, 1971.

TABLE 1
Simple Correlation Coefficients for Sediment Plume Variables[a]

Date	Variable	Sed.	DIC	Het.	P.Pr.	NO_3	PO_4	Fe	Light	Temp.	Cells	Basic Mass.
	Plume Density Units	−0.464				−0.712	−0.730					
	Suspended Sediment				0.556		0.709					
March 29, 1971	DIC					−0.686	−0.673					
(17 Degrees of Freedom)	Primary Productivity						0.597					0.523
	$NO_3 - N$						0.860					
	$PO_4 - P$											
	No. Cells · Volume^{-1}											0.490
	Plume Density Units	−0.819	0.845	−0.891	−0.625	−0.844	−0.802		0.709			
	Suspended Sediment		−0.907	0.898	0.686	0.965	0.921		−0.603			0.448
	DIC			0.872	−0.540	−0.931	−0.892		0.630			0.462
April 12, 1971	Heterotrophic Activity				0.733	0.893	0.898		−0.615			0.544
(17 Degrees of Freedom)	Primary Productivity					0.570	0.549					
	$NO_3 - N$						0.902		−0.604	−0.500		
	$PO_4 - P$								−0.645			0.610
	Light Penetration											
	Surface Temperature										0.457	
	No. Cells · Volume^{-1}											0.630
	Plume Density Units	−0.642	0.831	−0.818	−0.673				0.722			
	Suspended Sediment		−0.873	0.783					−0.682	−0.704		
June 7, 1971	DIC			−0.928	−0.660	−0.580	−0.432	−0.574	0.733			
(20 Degrees of Freedom)	Heterotrophic Activity				0.695	0.483		0.487	−0.819			
	Primary Productivity								−0.550			
	$NO_3 - N$						0.840	0.838				
	$PO_4 - P$							0.842				
	Fe											
	Light Penetration											
	Surface Temperature											
	No. Cells · Volume^{-1}											0.678

Date	Variable	Sed.	DIC	Het.	P.Pr.	NO_3	PO_4	Fe	Light	Temp.	Cells	Basic Mass.
	Plume Density Units	−0.766	0.755	−0.619	−0.561			−0.730	0.655			−0.581
	Suspended Sediment		−0.981	0.416	0.493			0.599	−0.704	−0.579	0.624	0.811
June 20, 1971	DIC			−0.495	−0.513			−0.556	0.661	0.601	−0.660	−0.854
Morning	Heterotrophic Activity				0.508	0.446		0.524				0.577
	Primary Productivity											
(21 Degrees of Freedom)	NO_3 − N						0.474	0.552				0.440
	PO_4 − P							0.689	−0.447			
	Fe								−0.631		0.443	0.623
	Light Penetration									0.636		−0.515
	Surface Temperature										−0.442	−0.544
	No. Cells · Volume^{-1}											0.867
	Plume Density Units	−0.752	0.776	−0.796	−0.695	−0.689	−0.456	−0.609	0.699	−0.620	−0.510	−0.576
	Suspended Sediment		−0.941	0.898	0.873	0.615		0.444	−0.713	0.469	0.538	0.890
June 20, 1971	DIC			−0.970	−0.791	−0.605			0.688	−0.489		−0.780
Afternoon	Heterotrophic Activity				0.721	0.572			−0.723	0.472		0.682
	Primary Productivity					0.683			−0.688		0.510	0.831
(21 Degrees of Freedom)	NO_3 − N						0.584	0.734	0.441	0.513	0.610	0.640
	PO_4 − P							0.919		0.674		
	Fe									0.715	0.460	0.443
	Light Penetration											0.576
	Surface Temperature											
	No. Cells · Volume^{-1}											0.637

[a] Direct and inverse relationships are indicated by positive and negative values respectively. Simple correlation coefficients near zero imply no correlation whereas simple correlation coefficients near 1.000 or-1.000 imply high direct or inverse correlations, respectively. Plume density units are such that low numbers correspond to high plume density. Thus, any relationship that would be direct in terms of plume density appears as an inverse one in terms of plume density units and vice versa. Confidence levels for correlation coefficients are indicated thusly: 0.xxx = ≥ 95%, 0.xxx = ≥ 99%, and 0.xxx = 99.9%. Simple correlation coefficients below 95% confidence level have been omitted for convenience.

ture. Warming of distal plume units again points to solar heating of suspended sediment. Correlations of temperature with a number of variables in Table 1 improved markedly over morning plumes possibly because high mouth temperatures created less pronounced double-valued functions.

Photometric measurements of light penetration were reduced to relative values to compare penetration with visual plume density. Relative values at each turbid water station were determined by dividing percent light penetration at the deepest measurement by percent light penetration at that depth in clear water. Such values consistently correlate well with plume densities, suspended sediment, and DIC (Table 1). Clear-water stations always had high relative light penetration values (0.7–1.0), while stations in dense plume units (1 or 2) always had low values (0.1–0.6). Stations with intermediate plume-density values (3, 4 or 5) usually had relative light penetration close to clear water. In many cases, such stations were indistinguishable. Similarly, plume units 1 and 2 could not be distinguished one from another. It appears color aerial photographs can be used more successfully than light penetration values to distinguish various degrees of turbidity.

Secchi disc readings could be made only in clear water deeper than 20 m or in very turbid shallow water. Disc readings could not be taken where the bottom was visible. Stations beyond the shelf had lower readings (18–34 m) than midlake stations (26–40 m).

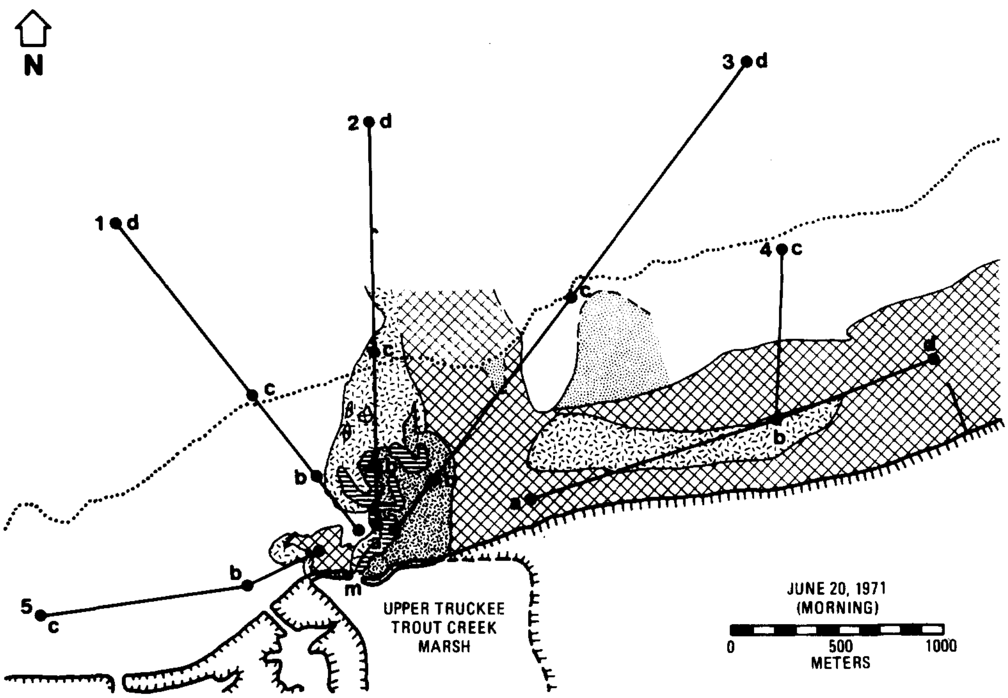
4. Heterotrophic Activity

It has been demonstrated that influence of the Upper Truckee River upon bacterial growth in Lake Tahoe is pronounced (Paerl and Goldman, 1972a). Growth has also been shown to increase from winter to summer. This is well illustrated by Figs. 4–7 where heterotrophic acetate assimilation in μg acetate $\cdot$ $m^{-3} \cdot h^{-1}$ is given for each station. Heterotrophic activity varied over two orders of magnitude and correlated with plume density, suspended sediment, DIC, and light penetration excellently (Table 1). Plots of heterotrophic activity vs. plume density units show a consistently strong relationship. Increased photographic capability enhances the spatial relationship between measured microbial activity and photographically detected water masses noted earlier (Paerl and Goldman, 1972a). Although values were low during April, the influence of the inflowing water was still readily detectable. Assimilation values were higher at the river mouth, directly north in the heart of the plume, and along the eastern shelf. June transects show a similar strong relationship between heterotrophic activity and plume shape and density. Transect assimilation values were higher. The double sampling on June 20 registered peak values during the sampling period and showed a distinct shift eastward in the afternoon.

5. Primary Productivity

Phytoplankton carbon assimilation rates relate to changes in plume density and configuration in a more irregular fashion than does bacterial activity. Still, primary productivity increased in areas influenced by the plume to the north and east of the river but remained low in clear water to the west. Higher values of primary productivity were observed in 1968 northeast of the mouth during synoptic studies (Goldman et al., 1972). Correlations of productivity with plume density, suspended sediment, DIC, and heterotrophic activity are good except for March 29 (Table 1). However, there are usually one or two stations in each study that exhibit markedly different primary productivity than expected based on plume density and heterotrophic activity values. We feel that discrepancies in primary productivity are due, in part, to physiological factors rather than physical conditions. For example, placement of phytoplankton from a turbid water environment in clear water for incubation could cause anomalous results since light values could be higher.

Productivity was greater in March than April at all but two stations. The plume was highly developed and evidently contained rain runoff from the March 26 storm. It probably carried a high nutrient load in melting snows from lower altitude urban areas. The plume was well developed in April but higher productivity was limited to the immediate river mouth area and a few areas to the northeast and east. Increased productivity occurred at all stations on June 7. Values were highest at the river mouth and decreased sharply to the west and less sharply eastward; no major discrepancies in primary



STATION	SUSPENDED SEDIMENT	DIC	HETEROTROPHIC ACTIVITY	PRIMARY PRODUCTIVITY
UTM	8.4	3.0	2539.8	28
1A	0.4	8.3	64.8	17
1B	0.3	8.6	70.5	19
1C	0.1	8.6	52.1	13
1D	0.1	8.7	27.4	16
2A	2.1	7.6	651.8	21
2B	6.1	5.8	1299.9	19
2C	0.3	8.6	62.5	9
2D	0.1	8.6	38.7	16
3A	8.9	3.8	36.8	33
3B	0.5	8.3	2868.4	32
3C	0.2	9.0	412.4	20
3D	0.1	8.6	80.8	9
4A	0.7	7.9	752.9	19
4B	0.5	8.1	274.8	18
4C	0.2	8.8	59.7	17
4D	0.4	8.2	274.1	35
5A	2.6	6.8	1059.3	20
5B	0.4	8.6	269.9	16
5C	0.2	8.4	70.8	9
5D	0.3	8.3	67.8	13
Mid Lake	0.1	8.6	28.9	9
Index	0.0	8.4	59.8	24

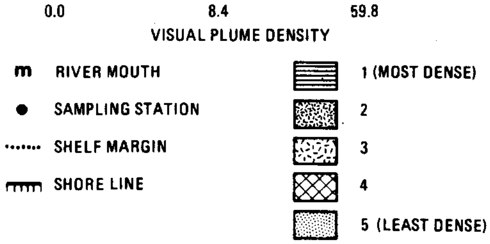
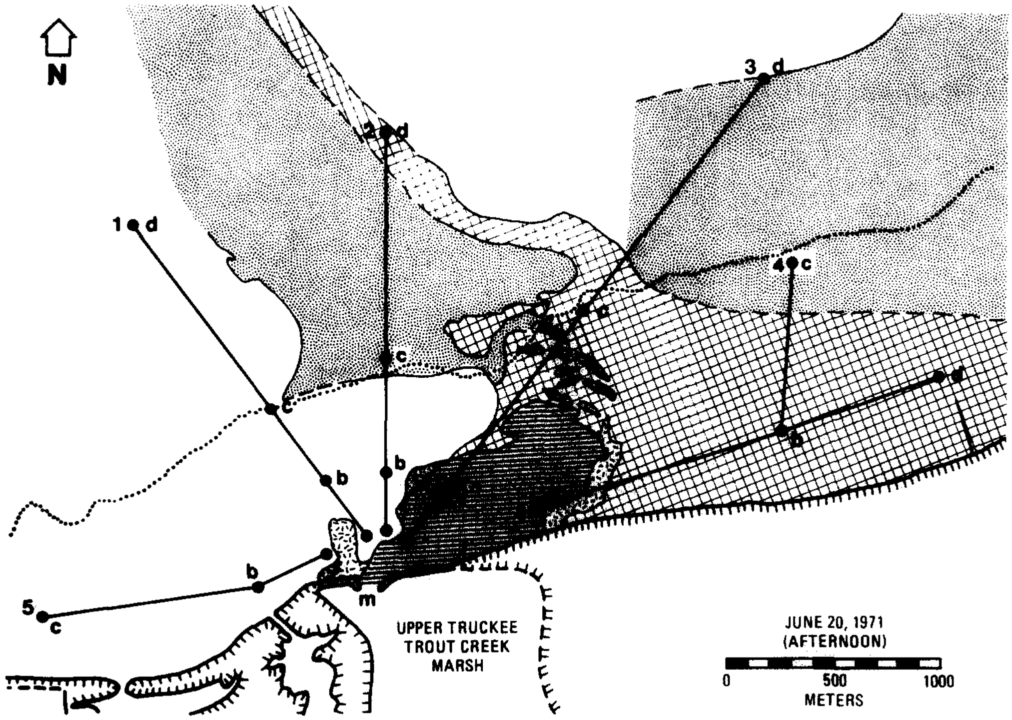


FIG. 6. Transect area at South Lake Tahoe showing the sediment plume for the morning of June 20, 1971.



STATION	SUSPENDED SEDIMENT	DIC	HETEROTROPHIC ACTIVITY	PRIMARY PRODUCTIVITY
UTM	9.5	2.6	2311.3	74
1A	0.7	8.8	30.9	19
1B	0.3	9.0	33.3	12
1C	0.3	9.0	34.1	32
1D	0.4	9.0	18.0	17
2A	0.7	9.0	46.6	17
2B	0.6	9.2	30.1	20
2C	1.3	9.0	43.0	12
2D	0.3	9.2	28.0	21
3A	4.7	6.0	1183.1	48
3B	2.7	7.8	623.8	42
3C	0.6	8.9	66.4	23
3D	0.5	8.9	19.6	14
4A	4.1	4.4	2437.4	27
4B	0.7	7.9	182.6	21
4C	0.5	8.6	88.5	26
4D	0.8	8.0	282.4	35
5A	3.2	7.5	678.7	38
5B	0.6	8.6	44.5	13
5C	0.2	8.7	56.8	13
5D	0.2	8.5	55.5	22
Mid Lake	-0.1	8.6	18.8	13
Index	0.2	9.1	47.2	23

VISUAL PLUME DENSITY

m RIVER MOUTH — 1 (MOST DENSE)
● SAMPLING STATION — 2
...... SHELF MARGIN — 3
SHORE LINE — 4
5 (LEAST DENSE)

FIG. 7. Transect area of South Lake Tahoe showing the sediment plume for the afternoon of June 20, 1971.

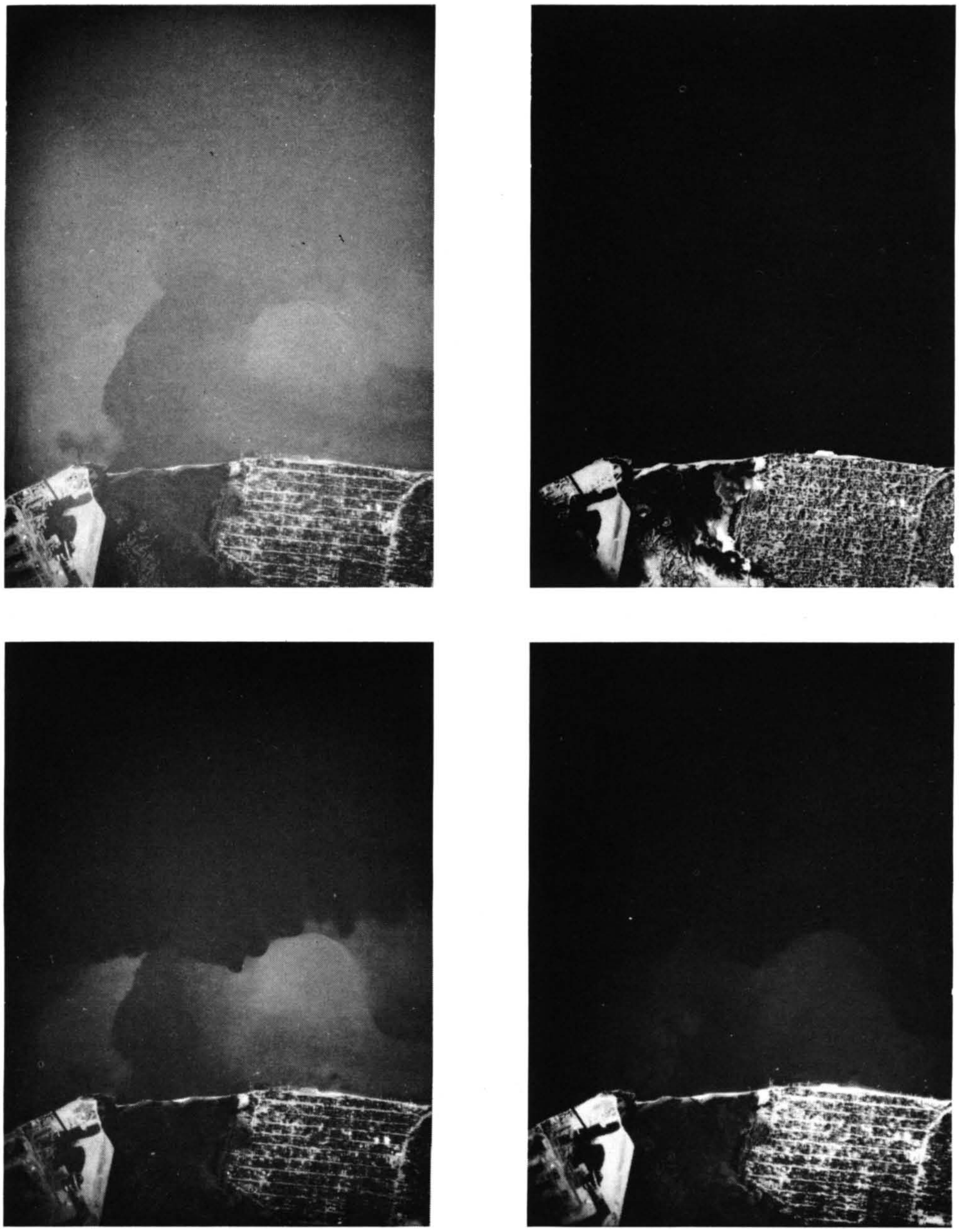


FIG. 8. Multispectral photograph of transect area of South Lake Tahoe showing sediment plume for the morning of June 20, 1971. Blue band–upper left; green band–lower left; red band–lower right; infrared band–upper right.

productivity compared to plume density and heterotrophic activity occurred. The morning sampling on June 20 resulted in lower values of phytoplankton growth rate but the pattern was less distinct (note lower confidence levels for productivity vs. sediment, DIC, and heterotrophic activity in Table 1). The afternoon sampling resulted in high correlations between plume density, heterotrophic activity, and primary productivity. The morning and afternoon studies confirmed that productivity as well as other indicative values were illustrative of the plume's eastward shift during the afternoon. This discovery is to some degree tempered by the fact that the incubation procedure differed (see methods).

6. Phytoplankton

Except for studies on June 20, correlations of the number of cells per unit volume or biomass with other parameters were almost nonexistent. It is unclear why good correlations exist only on June 20. The lack of consistent correlations emphasizes the differences between measures of standing crop and measures of metabolic activity or environmental conditions. Since biomass measurement required phytoplankton identification, it was possible to observe trends of various species by station location and throughout the period of study. The trends were not tested by simple correlations but the observations follow.

The largest biomass level for any of the studies was recorded on March 29. There were distinct differences in phytoplankton community composition between near and off-shore stations for that plume. The phytoplankton community of each station was dominated by three or four diatoms which were the major biomass contributors except in close proximity to the river mouth. *Cyclotella bodanica*, *Melosira crenulata*, and *Synedra radians* were usually the most abundant species. *Synedra radians* provided the single largest biomass component. Other diatoms such as *Asterionella formosa*, *Fragilaria crotonensis*, and the Chrysophycean *Dinobryon sertularia* were abundant locally and together with *Cryptomonas reflexa*, *Euglena* sp., and some flagellates were responsible for most differences in phytoplankton composition detected near the river mouth. The greatest measured cell concentration and biomass occurred just to the east of the inflow where the highest primary productivity was found (Fig. 3).

Early April sampling revealed a similar phytoplankton composition with *Synedra*, *Cyclotella*, and *Melosira* dominating. *Asterionella* appeared again close to the river mouth but *Dinobryon*, which had also been an indicator of plume location, was much less prevalent. *Cryptomonas*, *Euglena*, and the flagellates were not present. *Melosira* was more abundant in the plume than at locations to the west. Samples to the northeast and around the river mouth contained the largest biomass. Total values were lower than those in March.

The June 7 sampling was marked by a definite decrease in dominance of the major diatoms and by important but isolated appearances of the green algae *Staurastrum paradoxum* and some other diatoms, such as several species of both *Achnanthes* and *Epithemia*. There was a significant resurgence of *Dinobryon* and a very large increase in *Peridinium* sp. and flagellates at most sampling locations. *Asterionella formosa* was present in samples near the river mouth but also occurred in many samples within the plume influence to the east and north. Consistent with the higher primary productivity, there was a larger number of cells but with lower biomass than in April; the highest values of both occurred east of the river mouth.

The two samplings on June 20 revealed a continuing trend toward greater community diversity along with subsidence of previously abundant forms and *Staurastrum*. *Dinobryon* became much more abundant and so did another Chrysophycean, *Kephyrion ovum*. Flagellates were present in a fan-shaped pattern north of the river mouth but did not appear to the east or west along the shoreline. In contrast to *Asterionella*, which again was locally abundant in the plume, *Dinobryon* showed a general increase in numbers with increasing distance away from the plume. *Peridinium* was abundant at almost all stations. Many diatom species were present at the river mouth, both in the morning and afternoon, possibly indicative of the dynamic nature of the sampling area and mixing of water and phytoplankton from both lentic and lotic environments. Cell numbers and biomass increased in the afternoon, and there was a distinct shift of the phytoplankton population east of the river mouth during the day, concurrent with visible evidence of plume movement. Total cell numbers were lower than on earlier dates but biomass decreased only slightly.

IV. Discussion

Sediment plume of the Upper Truckee River can be mapped for both position and density a considerable distance into Lake Tahoe by aerial photography and simultaneous field collections of water truth data. Several chemical and physical parameters correlate with mapped plume positions and densities. Most importantly, biological measurements of bacterial and phytoplankton activity clearly show the influence of the plume. These measures of biological activity are particularly useful in assessing eutrophication processes. Bacterial activity is strongly related to increasing plume density as the Upper Truckee River mouth is approached. We suggest that suspended detrital material, issuing from the river mouth, stimulates bacterial growth because it simultaneously provides attachment surfaces for bacterial adhesion and a concentrated nutrient source. Bioassay experiments with nutrient stripped, sterile silt added to midlake water provided attachment surfaces and showed striking amounts of stimulation over midlake water without silt (Paerl and Goldman, 1972b). These experiments were conducted with similar final concentrations of organic and inorganic nutrients, thus proving that surface area is of prime importance to promotion of bacterial growth. In addition to surface area, the high nutritive content of silt in the sampling area (NO_3^{-1}, PO_4^{-3}, organic carbon) further boosts bacterial growth. Additional evidence of bacterial attachment comes from microautoradiographic experiments showing bacteria actively assimilating heterotrophic substrates while attached to silt (Paerl and Goldman, 1972a). It would appear that attached bacteria utilize nutrients from silt as well as solution.[1]

Through mineralization, nutrients are eventually available for later uptake by phytoplankton. In addition, the hundred-fold change of heterotrophic activity caused by sediment plumes raises the possibility that a minor biomass component, bacteria, may have major effects on eutrophicating processes, namely breaking down organic sediment to release nutrients for algal growth (Paerl and Leonard, unpublished).

The relationship between phytoplankton productivity and mapped plume density is less dramatic but the correlation varies between 99% and 99.9% confidence levels except for March 29. Lack of correlation on that date, we feel, is due to an hour's time lag between photographic observation and beginning aquatic sampling; field notes indicate a plume shift sufficient to change the character of the water mass at a number of stations. Subsequent studies commenced aerial and aquatic efforts simultaneously, albeit for other reasons. Phytoplankton utilize dissolved nutrients and not those attached to silt as do heterotrophs. In view of spotty correlations between plume density and dissolved nutrients, which may be caused by biological utilization (see below), it is not surprising that primary productivity displays lower correlation than heterotrophic activity with plume density.

Nutrients under plume influence owe their changes, in part, to biological processes which utilize them. Lake Tahoe contains very low concentrations of nutrients and primary productivity has been proven to be nitrogen and iron limited (Goldman and Armstrong, 1969; Goldman, 1964). Biological utilization may well have contributed to the spotty correlation with plume density. Changing concentrations of these nutrients during June 20 may be linked to both increased inflow of nutrients from the river as well as biological utilization.

Changes in phytoplankton diversity, cell numbers, and biomass were indicative of the Upper Truckee River sediment plume. But while they signaled the changing seasonal conditions in the lake, the relationship of these phytoplankton characteristics to plume density is unclear. Only during June 20 was there a strong correlation (Table 1) between plume density units and total cell numbers or biomass. Unless inflow brings in new species and/or greater numbers of phytoplankton the change in plume configuration is too rapid to produce a good correlation between phytoplankton and plume density. However, it is clear from the data that certain algal species are quite indicative of plume presence. Several types are either excluded from the area adjacent to the river mouth or are more abundant than in other areas. It is apparent that phytoplankton community changes, although useful indicators, taken alone cannot define the effects that a tributary has on Lake Tahoe.

Good correlations between photographic and

[1] An alternate explanation of the heterotrophic activity-plume density relationship is that the bacteria attached to silt particles derive from the original soil. Hence, good correlation between the two parameters would be caused by the fact that soil bacteria are always attached to the silt. However, the above experiment with sterile silt showed stimulation of midlake bacteria as opposed to soil bacteria. Secondly, the bacteria continue to survive and multiply in the lake environment so that any effect on the lake is identical irregardless of their origin.

aquatic data imply that it is reasonable to assign similar values to various water parameters in unsampled areas. The values can be assigned to mapped units with a certainty corresponding to the degree of correlation (Table 1). High heterotrophic activity represents plume units of high density and the activity of even the least-dense units will be higher than clear water. The data also suggests that the Upper Truckee River sediment plume probably causes higher than normal levels of primary productivity to extend over much of the southeastern corner of the lake. Photographs show that the sediment plume grows from early spring to reach its maximum size during peak river discharge. Our data indicate that primary productivity followed a similar development and that the Upper Truckee River plume has become a permanent influence on algal growth in the lake.

Spatial and temporal association of high biological activity with the Upper Truckee River sediment plume is circumstantial evidence that the sediment plume is the causative agent but additional evidence must be added to demonstrate a causal relationship. The strong relation between plume densities, suspended sediment, and heterotrophic activity coupled with the evidence for bacterial attachment to and nutrition by sediment particles is strong evidence for stimulation caused by sediment particles. The link between plume densities and primary productivity, while less dramatic, is important because it measures actual algal growth rate in the lake. Good correlations exist between primary productivity and plume density; plume density is correlated with nutrients for the first two and last studies but biological utilization may have destroyed the correlation for the other two as well as that between primary productivity and nutrients. Previous work (Goldman and Armstrong, 1969) showed high nutrient levels in Upper Truckee River water (such as were consistently measured at the mouth station in this work) increased primary productivity in the lake's water. Taken together, the two lines of evidence indicate that the nutrients associated with the sediment plume are the causative agents of increased primary productivity. Thus, both measures of biological productivity indicate that the sediment plume is the causative agent of increased production.

V. Conclusions

Aerial photographs and simultaneous on-site water samples in Lake Tahoe can be used to document temporal and spatial influences of the Upper Truckee River sediment plume on a yearly or daily basis. DIC and heterotrophic activity are highly correlated with photographic evidence and appear to be especially promising methods of water mass delineation. Nutrients, sediment load, light penetration, temperature, phytoplankton community changes, and primary productivity can also be useful when samples are numerous enough for correlation with photographic records.

Relationships between the sediment plume and both primary productivity and bacterial activity implicate sediment particles and associated nutrients with more rapid nutrient utilization and growth by bacteria and phytoplankton. Coupled with these findings, we note the sediment load in the Upper Truckee River from man-made disturbances in its watershed is increasing. We believe that land disturbance is contributing further to accelerated eutrophication of Lake Tahoe.

Methods described here should be applicable to other situations where tributary inflows to a river or lake are visibly different in clarity. Collection of similar baseline limnological information is a continuing necessity for proper interpretation of tributary influences evidenced by photographic data.

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