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Publication Date

1983-03-01

W548

EVALUATING THE INFLUENCE OF GEOCHEMICAL ORIGIN AND DROUGHT CONDITIONS ON AQUATIC BIOTA OF THE GEYSERS KNOWN GEOTHERMAL RESOURCES AREA OF CALIFORNIA

by

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The research leading to this report was supported in part by the United States Deparment of the Interior, under the Matching Grant Program of Public Law 95-467, Project No. B-200-CAL, and by the University of California Water Resources Center, Project UCAL-WRC-W-548.

TECHNICAL COMPLETION REPORT

March 1983

ABSTRACT

From 1976-1983, a series of studies were undertaken at The Geysers K.G.R.A. in Sonoma and Lake Counties, California to evaluate the effects of geothermal energy development on aquatic biota at The Geysers. A major objective throughout the eight years of the research project has been to develop quantitative methods to analyze and monitor benthic communities. This report summarizes the methods used and presents examples of the data such approaches have produced.

Each report on a sampling approach contains: (1) a summary of the advantages and disadvantages of the device; (2) an illustration of the device; (3) a description of its use either at The Geysers or in pilot studies to test the appropriateness of its use at The Geysers; and (4) a sample data set.

TABLE OF CONTENTS

I. Introduction

II. Direct Substrate Sampling

1. Surber Sampler
2. Reduced Quadrat
3. Drift Net
4. Hyporheic Corer
5. Freeze Corer
6. Egg Sampler
7. T-Sampler

III. Artificial Substrate Sampling

1. Artificial Substrate Tile
2. Hyporheic Pot
3. Substrate Implant
4. Colonization Trap - Oviposition
5. Colonization Trap - Upsteam Movement
6. Colonization Trap - Drift
7. Colonization Trap - Hyporheic Movement

IV. Non-Disruptive Sampling

1. Visual Counts
2. Photography
3. Pupal Clump Counts

V. Adult Sampling

1. Pan Trap
2. Pheromone Trap
3. Ultraviolet Light Trap
4. Emergence Trap

VI. Field Experiments

1. Stream Microcosms
2. Heat Shock Field Experiment
3. Primary Production

VII. Analytical Methods

1. Calibration of Artificial Substrates
2. Computer-Aided Dispersion Analysis
3. Elutriation
4. Sequential Sampling

VIII. Literature Cited

IX. Assessing Drought Effects on Geothermally Influenced Streams

X. Comparison of Seston Dynamics in Two Geothermal Basins

XI. Acknowledgment

I. INTRODUCTION

Geothermal effluents contain substances that can potentially affect both terrestrial and aquatic organisms. The sources of effluents from geothermal energy production include: (1) steam from well blowouts and uncapped wells; (2) drift and blowdown from cooling towers; (3) condensation from steam lines; and (4) discharge from hot water wells. These effluents are typically heated, extremely saline, and contain high concentrations of toxic substances such as arsenic, ammonia, hydrogen sulfide, boron, and mercury. The full utilization of our indigenous geothermal resources depends on the development of environmentally acceptable operational practices that minimize the biotic effects of these effluents.

The largest operational geothermal power project in the world is located at The Geysers, approximately 100 km north of San Francisco, California, and within the Known Geothermal Resources Area (K.G.R.A.; Fig. I-1A). Fifteen geothermal power plants are currently in operation at The Geysers and produce about 1000 Mw of electricity. Although the United States has embarked on a progressive program to efficiently develop its indigenous geothermal resources, virtually all of the geothermal power production is currently limited to the K.G.R.A. Potentially rich sites in the Imperial Valley of California, the Great Basin (including areas of several western states), and the K.G.R.A. itself have been hindered by conflicting evaluations of potential environmental disruption associated with the development, operation, and construction of geothermal power plants.

From 1976-1983, a series of studies were undertaken at The Geysers K.G.R.A. in Sonoma and Lake Counties, California, to evaluate the effects of geothermal energy development on aquatic biota at The Geysers. A major objective throughout the eight years of the research project has been to develop quantitative methods to analyse and monitor benthic communities. This report summarizes the methods used and presents examples of the data such approaches have produced.

Several monographic treatments on related research topics have already resulted from this project. Resh (1979a) reviewed sources of benthic sampling biases, and ways of reducing the effects of those confounding factors when developing experimental designs. Waters and Resh (1979) examined ecological and statistical features that influence the sampling of benthic organisms, and compared them with approaches used in sampling forest environments. Rosenberg et al. (1981) examined recent trends and future needs in the process of environmental impact assessment. Rosenberg and Resh (1982) provided a detailed review of the use of artificial substrates in freshwater macroinvertebrate studies, especially in biomonitoring. Lamberti and Resh (in review) coupled *in situ* and microcosm techniques to experimentally separate the effects of the thermal and chemical components of geothermal fluids on stream benthic communities at The Geysers.

Shorter works have examined the relationship between taxonomy and species diversity in the biomonitoring process (Resh 1979b), interactions between periphyton and insect herbivores (Lamberti and Resh 1983), geothermal influences on a caddisfly population (Resh et al. 1981), "non-disruptive" population sampling (Lamberti and Resh 1979), and sampling devices for use in different types of habitats (Merritt et al. 1979, 1983).

This research was primarily conducted in Big Sulphur Creek, Sonoma Co., California (38° 47' N, 122° 47' W; elev. 670 m), a third-order stream that flows northwest through The Geysers K.G.R.A. (Fig. I-1B). Several of the studies described in this report were conducted at the confluence (M) of Big Sulphur Creek and its tributary, Little Geysers Creek (Fig. I-1C). Big Sulphur Creek is a cold (i.e. non-geothermal) stream upstream (U) of that point; Little Geysers Creek is a heated (i.e. geothermal) stream formed by a number of small hot springs. Therefore, Big Sulphur Creek also becomes a geothermally influenced stream downstream (D) of that input.

For each sampling approach used at The Geysers and described in this report, we present: (1) a summary of the advantages and disadvantages of the device; (2) an illustration of the device; (3) a description of its use either at The Geysers or in pilot studies to test the appropriateness of its use at The Geysers; and (4) a sample data set.

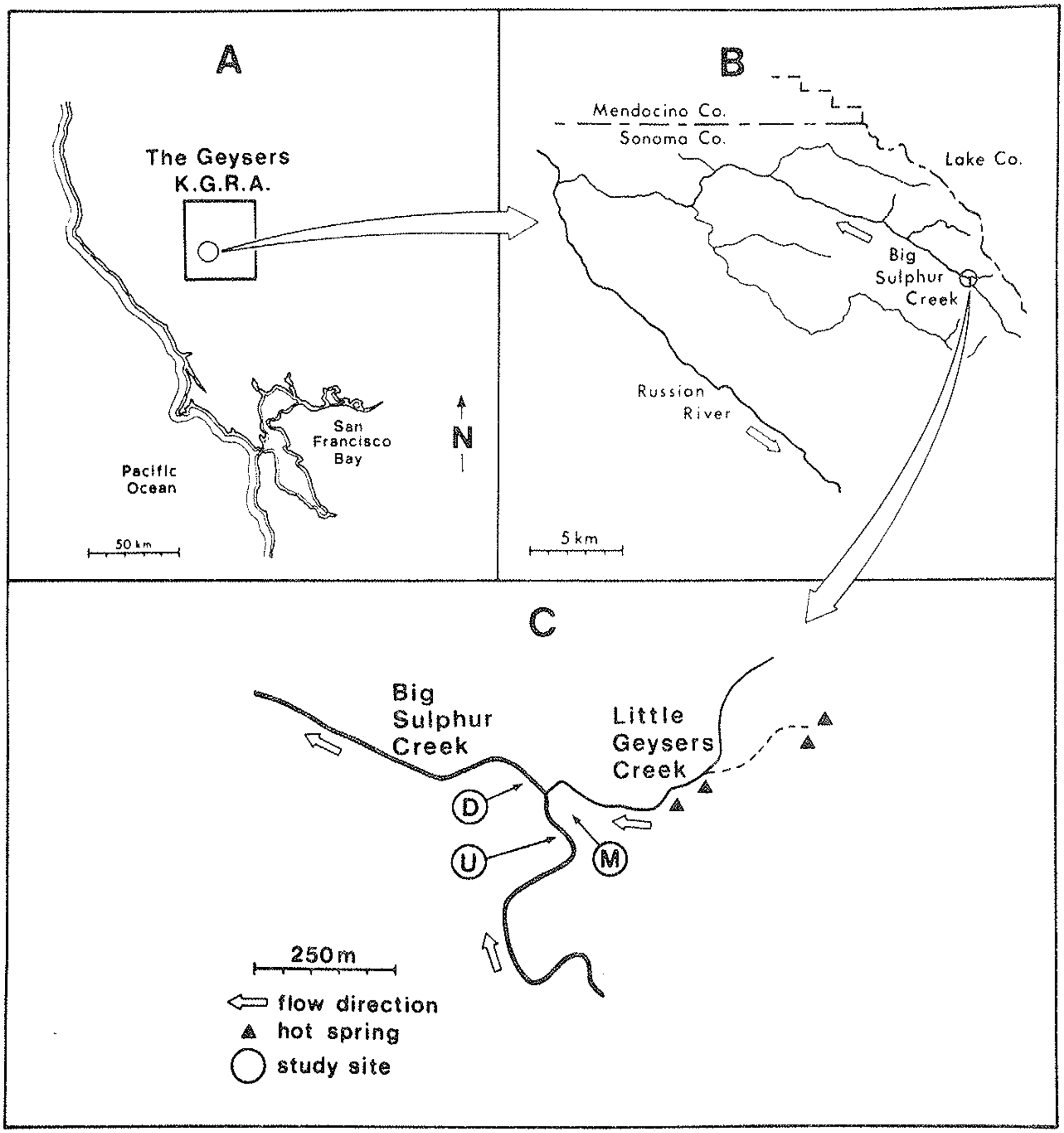

A
The Geysers
K.G.R.A.
Pacific
Ocean
San
Francisco
Bay
N
50 km
B
Mendocino Co.
Sonoma Co.
Lake Co.
Big
Sulphur
Creek
Russion
River
5 km
C
Big
Sulphur
Creek
Little
Geysers
Creek
D
U
M
250 m
flow direction
hot spring
study site

Figure I-1

II-1. SURBER SAMPLER

Perhaps the best known sampling device for shallow running water habitats is the Surber (1 ft^2; 0.093 m^2) sampler (Fig. II-1; Surber 1937). Although its usefulness has been periodically questioned (e.g. Kroger 1972), the Surber sampler remains a standard collecting device for many studies. The sampling variability associated with the use of the Surber sampler has been discussed by Needham and Usinger (1956), Chutter (1972), and Resh (1979a).

We used the Surber sampler for both community- and species-level studies in Big Sulphur Creek at The Geysers. Sample nets had mesh sizes of 10 threads/cm (25/in). Stream community studies using this device revealed that, in an area of long-term geothermal development (LTD), the number of macroinvertebrate species decreased with the addition of thermal(T), chemical(C), and silt (S) effluents (Table II-1). However, the total number of individuals increased along that gradient; much of that increase was due to the positive responses of two caddisfly (Trichoptera) species, _Gumaga nigricula_ (McLachlan) and _Helicopsyche borealis_ (Hagen) (Resh et al. 1981).

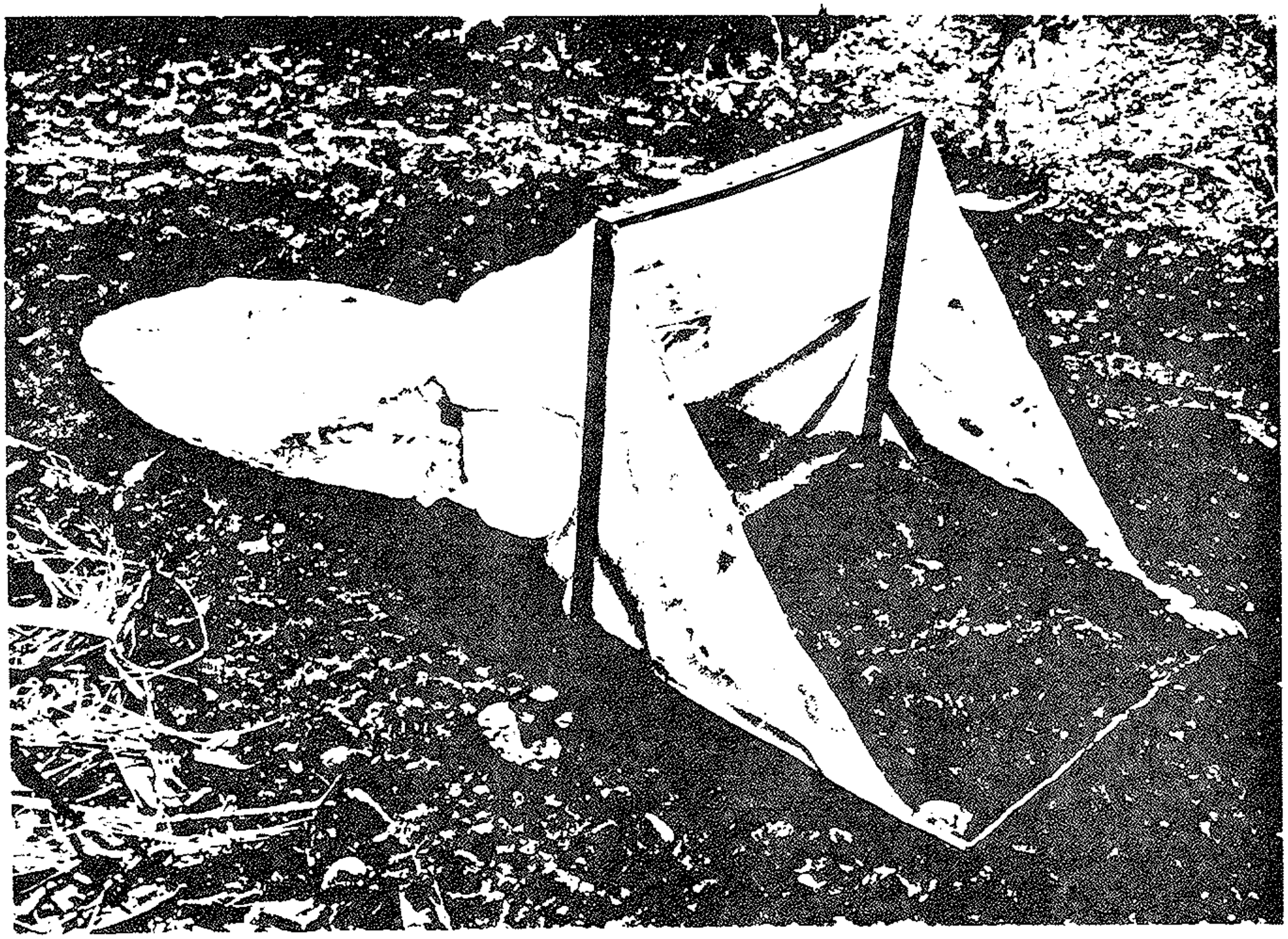


Figure II-1

TABLE II-1

	$\overline{X}$ NO/0.093 M^2			
	SPECIES	INDIVIDUALS	*HELICOPSYCHE*	*GUMAGA*
LTD	29	634	58	66
LTD+T	20	644	176	178
LTD+T+C+S	14	1,085	373	301

II-2. REDUCED QUADRAT

Although the quadrat size of a standard Surber sampler is normally fixed (i.e. 1 ft^2; 0.093 m^2), we have modified that sampler for use in small, spring habitats (Fig. II-2A). For example, in studies of cold springs near Hopland, Mendocino Co., CA (e.g. Resh 1982, Resh 1983) that are smaller in width than the Surber sampler, we have reduced the size of the quadrat to 158 cm^2, 17% of the original sampler area. An additional advantage of this reduction is that larger numbers of samples can be collected in these habitats, without the habitat disruption that may result if many standard-sized samples were collected. Since the volume of the sample is reduced, sorting time also decreases.

Zonation in macroinvertebrate species diversity ($\bar{H}$) was observed from the analysis of 54 158-cm^2 samples collected along a freshwater spring near Hopland, CA, which is located about 35 km from The Geysers. As distance from the spring source increased, species diversity decreased (Fig.II-2B). These results indicate that significant variation may occur in the same firt-order stream habitat, which must be considered in designing sampling programs. An advantage of using a reduced quadrat size is that sufficient numbers of samples can be collected to determine if zonation patterns are present.

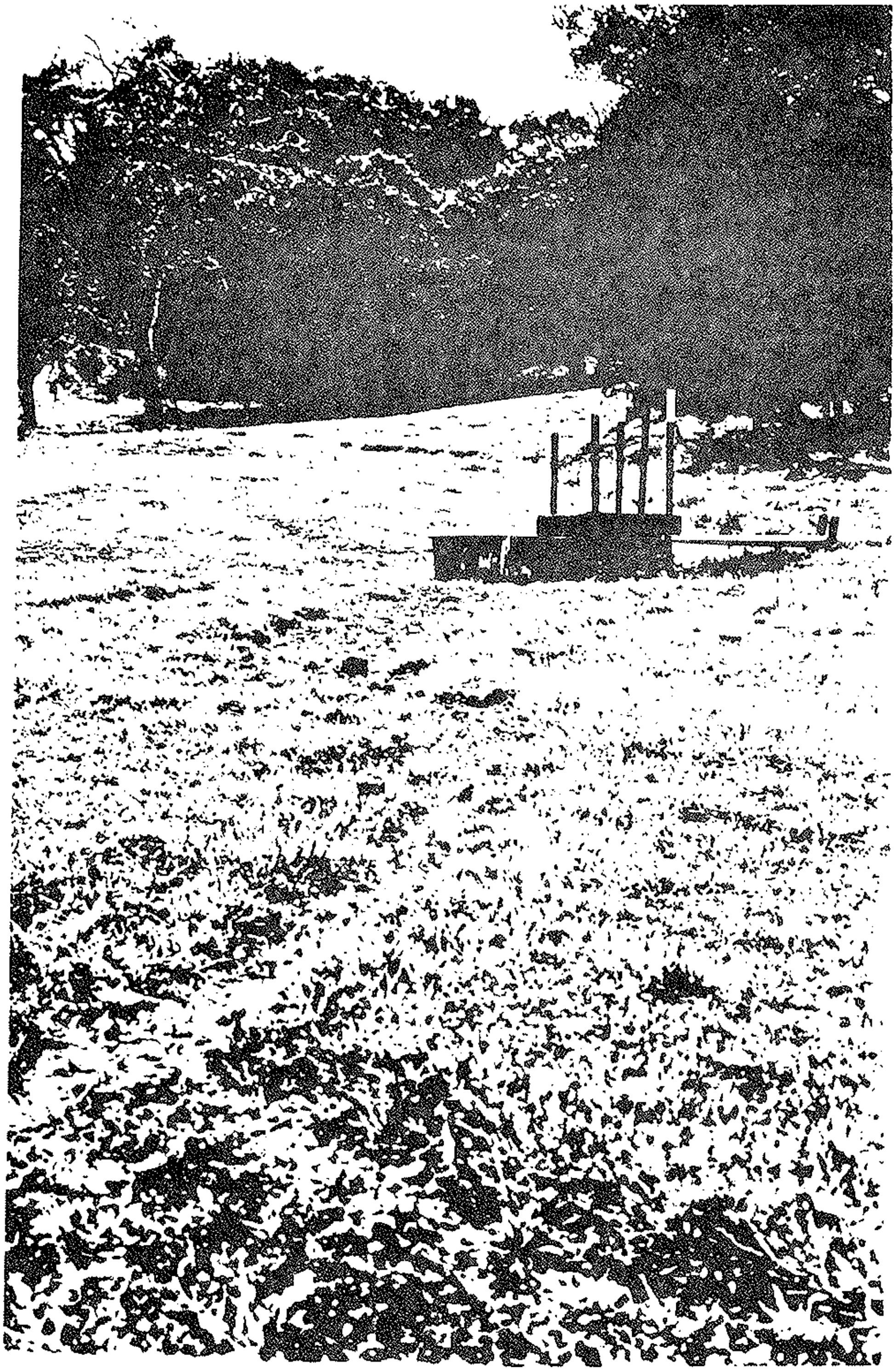


Figure II-2A

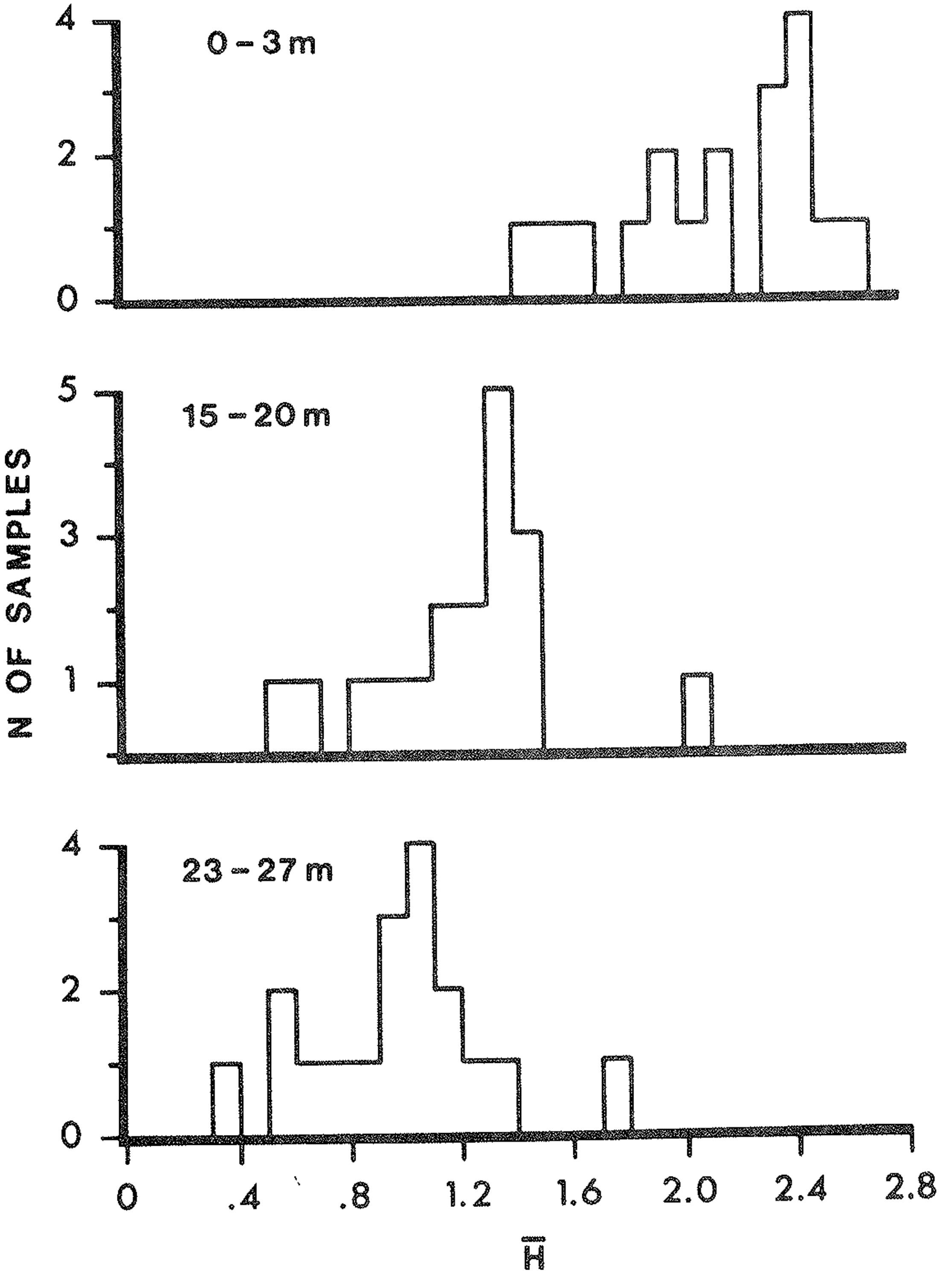


Figure II-2B

II-3. DRIFT NET

The downstream displacement (drift) of aquatic organisms is common to all running waters and has been attributed to both behavioral and catastrophic causes (Waters 1972). A large number of sampling devices have been described for studying this phenomenon (e.g. Elliott 1970, Merritt et al. 1978, 1983). The geothermally heated waters in the Big Sulphur Creek (BSC) drainage at The Geysers afforded the opportunity to study decolonization by the drift process. During mid-summer, a lethal thermal zone forms in Little Geysers Creek (LGC), a geothermal tributary to BSC, and induces catastrophic insect drift. By determining the mechanisms responsible for this natural seasonal process, insights into the effects of geothermal development-related disruptions may result.

We designed a simple drift net (Fig. II-3), after comparing the many varieties described in the scientific literature (e.g. Elliott 1970). The aperture of the net was sufficiently large (530 cm^2) to sample the entire depth of the water column. A quick-change collar and long (1 m) net were used because of the abundant algae drifting from the heated sections of LGC. In thermally stressed segments of LGC, >97% of all drifting macroinvertebrates were chironomid midge larvae (Diptera) and oligochaetes (Table II-3). In addition, the normal drift pattern was not present; typically, stream drift peaks during the night (e.g. Elliott 1970). In LGC, peak drift of chironomids occurred during early afternoon, corresponding to the period of highest daily stream temperature. The peak drift of oligochaetes occurred during the late morning, possibly indicating a lower thermal threshold for these organisms.

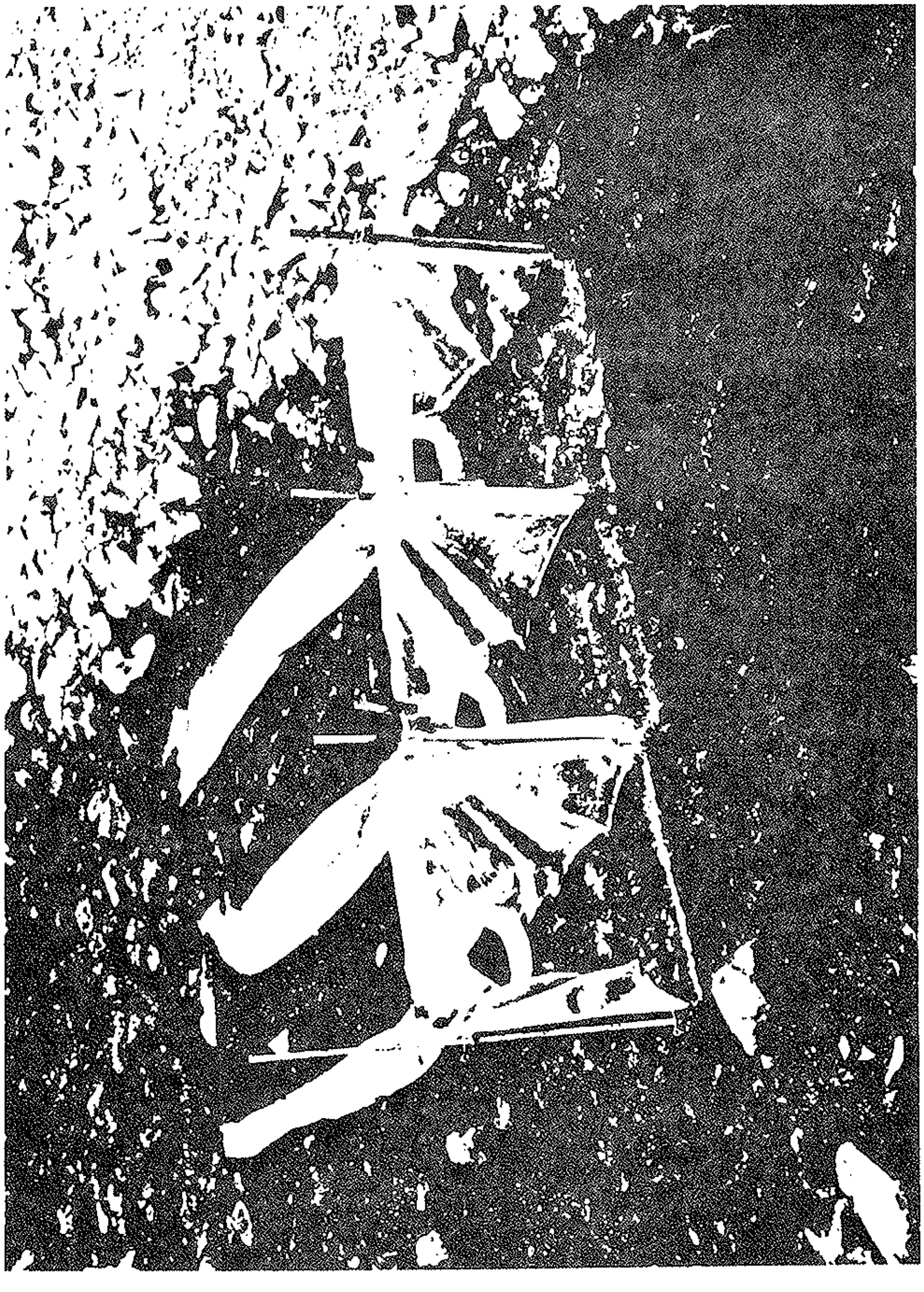


Figure II-3

TABLE II-3

	LGC 1-H DRIFT (22-23 MAY 1982)		
Time Period (H)	Chironomidae (% 24-h total)	Oligochaeta (% 24-h total)	Individuals (total no.)
1930-2030	2.0	3.8	12,465
2230-2330	0.5	10.0	11,420
130-230	0.3	9.8	10,089
430-530	0.3	7.1	7,593
730-830	1.3	9.9	14,879
1030-1130	9.2	45.1	82,140
1330-1430	77.8	7.3	361,246
1630-1730	8.6	6.9	45,527
24-h Total	455,940	89,419	545,359

II-4. HYPORHEIC CORER

Hyporheic populations (i.e. those organisms located >5 cm deep in the substrate) can comprise a significant portion of stream insect communities (Coleman and Hynes 1970, Williams and Hynes 1974). One of the most effective methods of sampling hyporheic organisms in the stream bottom is to take a vertical core of the substrate. Coring techniques overcome many of the problems inherent in artificial substrate methods that require long colonization times. Williams and Hynes (1974) described a 2.5 cm-diameter coring device that could efficiently obtain a small (25 ml) sample of substrate from any 10 cm depth horizon. In our design, we increased the diameter of the corer to 3.8 cm to obtain a 50 ml substrate sample (Fig. II-4).

For sampling hyporheic communities in Big Sulphur Creek (BSC) at The Geysers, the corer was of limited use because cobble and boulders in the substrate halted its penetration. Therefore, the corer was used only in reconnassance studies of the hyporheic community (Table II-4). In a transect across a large pool of BSC, low numbers and species of macroinvertebrates were collected from the 20-30 cm-deep stratum. This corer was later abandoned in favor of artificial substrate methods (see Section III-2).

Figure II-4

TABLE II-4

TRANSECT STATION (20-30 cm)	INDIVIDUALS (no/50 ml)	SPECIES (no/50 ml)
1	4	4
2	0	0
3	2	2
4	4	4
5	0	0

II-5. FREEZE CORER

An alternative method for taking a hyporheic sample from a streambed is to use a liquified gas (such as N_2, O_2, or CO_2) to freeze the substrate (e.g. Stocker and Williams 1972). The solidified mass is then removed mechanically, producing a vertical substrate "core". Macroinvertebrates are assumed to be trapped within this core, although there is some question about whether organisms move out of the sample area during cooling (Stocker and Williams 1972). However, Williams (1983) reports that this method has been used effectively in Europe.

At The Geysers, we used the liquid CO_2 freeze corer described by Walkotten (1976). A copper probe is driven into the streambed (Fig. II-5), from which liquid CO_2 escapes through numerous small holes to cool the surrounding substrate. The CO_2 device was selected for its ease in handling and the ready availability of liquid CO_2 in cylinders or fire extinguishers. Unfortunately, this device was not effective in Big Sulphur Creek when summer sampling was attempted, because the warm substrate in this geothermally influenced stream could not be sufficiently cooled to produce a cohesive core.

Figure II-5

II-6. EGG SAMPLER

Light weight objects on the stream bottom are difficult to sample because water displacement caused by the movement of the sampling device or by the operator resuspends low density particles into the water column. Since many aquatic insects broadcast their eggs or egg masses across the water surface, these eggs sink to the bottom, where they collect behind obstructions, in algal mats, or in the interstices of the gravel bottom. A type of cylinder sampler was used at The Geysers to reduce the bias associated with sampling insect eggs (Fig. II-6). This 0.1-m^2 circular sampler was constructed by adapting a traditional design for the Hess sampler (Jacobi 1978).

We discovered at The Geysers a unique egg mass produced by the caddisfly _Gumaga_ _nigricula_ (Wood et al. 1982). The distinctive "U"-shape of this egg mass is easily recognizable in benthic samples. This new egg sampler was used during the spring flight period of _G_. _nigricula_. Samples were taken from transects across the head, middle, and tail of a pool in Big Sulphur Creek (Table II-6). Oviposition habits and water current velocities produced an aggregated distribution of _G_. _nigricula_ eggs. Failure to consider the egg stage in ecological studies can result in significant underestimates of secondary production. Data from egg sampling provides the information that is usually lacking in production and population dynamics studies.

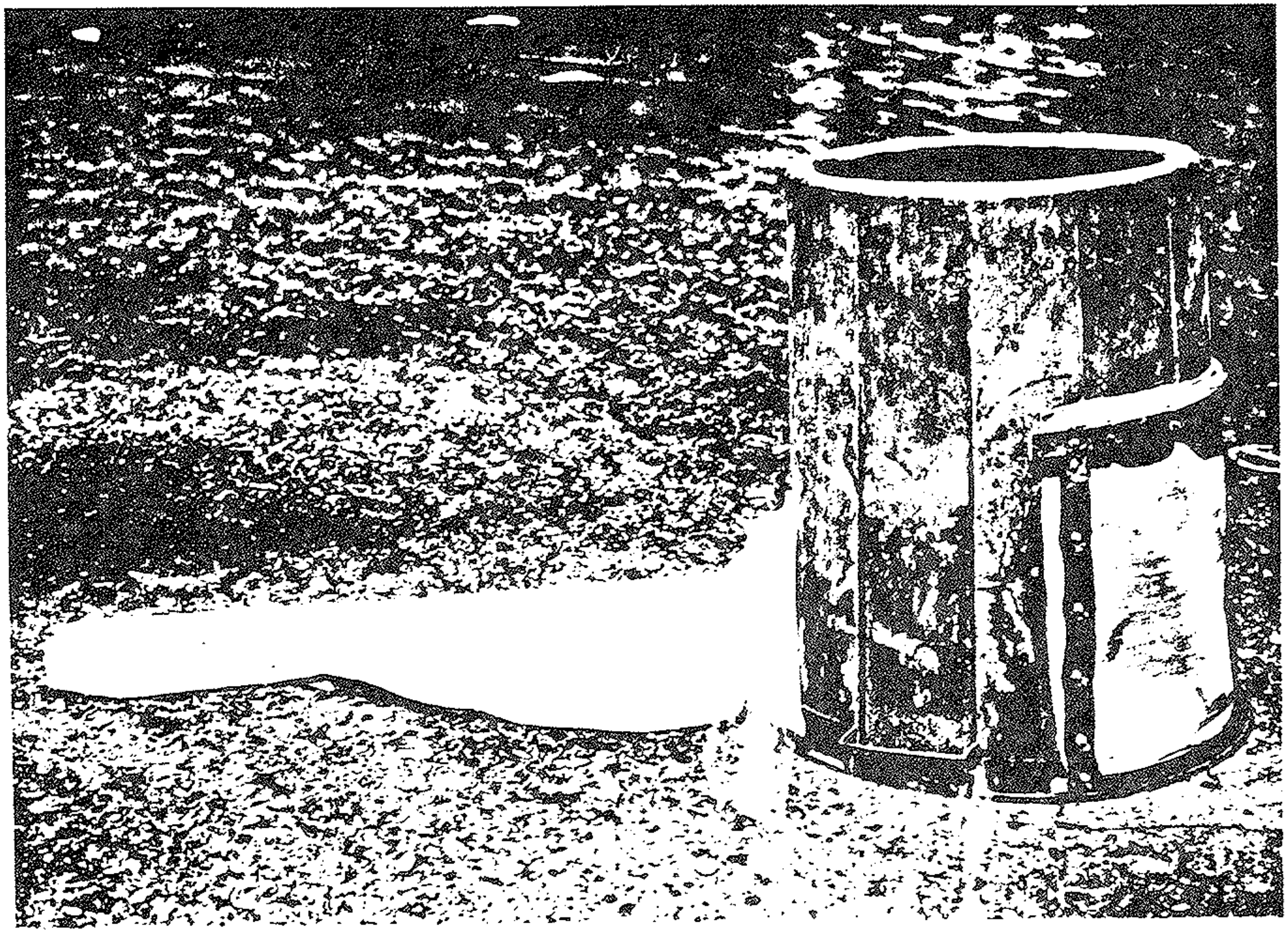


Figure II-6

TABLE II-6

GUMAGA EGG MASSES/0.1 M^2

Transect	1	2	3
$\overline{x}$	8.8	38.8	47.3
SD	15.8	75.1	15.8
range	0-41	2-191	0-41
n	6	6	6

II-7. T-SAMPLER

The use of a completely enclosed type of surface substrate sampler has been recommended to reduce the sampling variability associated with the open-front Surber sampler. A number of circular sampling devices have been devised for sampling a variety of running water habitats (Southwood 1978). The T-sampler was described by Mackie and Bailey (1981) and was used at The Geysers to study the population dynamics of the caddisfly *Gumaga nigricula* in Big Sulphur Creek (Fig. II-7).

The T-sampler was used in a transect sampling design in a pool that was influenced by geothermal energy development. The small size of the sampler (diameter = 9.8 cm) increased the efficiency of both field and laboratory sample processing; thus, additional samples could be taken with little increased expense. By sampling *G. nigricula* populations during October and February (Table II-7), we determined that larvae were evenly distributed across the width of the stream in autumn; however, during winter, larvae migrated to the stream margin where they overwintered on the root balls of streamside vegetation. Development-related activities that modify this portion of the stream habitat may directly affect winter survivorship of *G. nigricula* larvae.

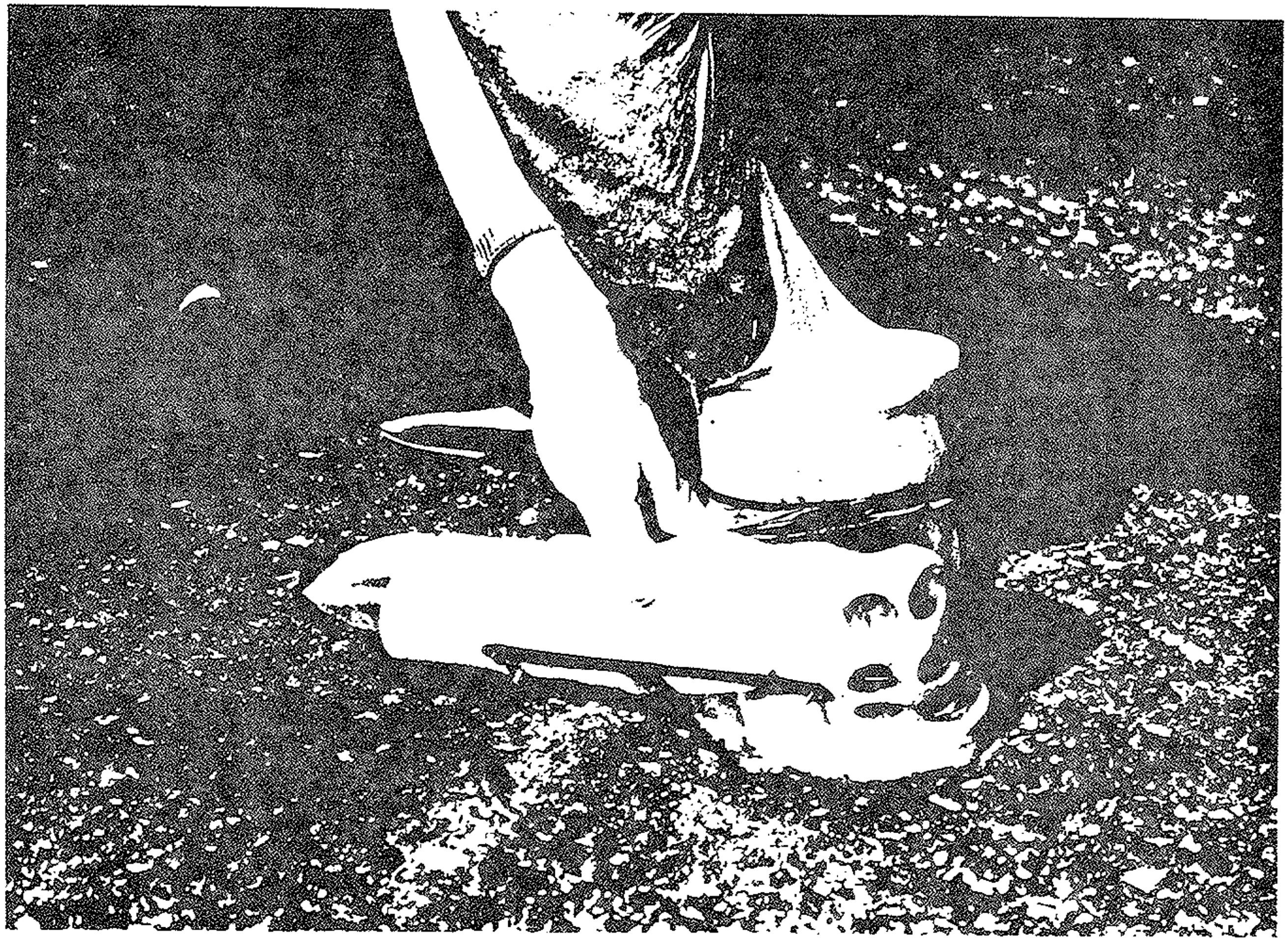


Figure II-7

TABLE II-7

DISTANCE FROM SHORE (M)	$\overline{X}$ *GUMAGA* LARVAE/0.1 M^2 October 1981	February 1982
0.3	46.8	6.2
0.9	29.6	4.7
1.8	46.8	2.4
2.7	34.4	<1.0
3.6	31.2	<1.0
4.5	34.4	<1.0

III-1. ARTIFICIAL SUBSTRATE TILE

Artificial substrates are items that mimic certain features of the aquatic habitat in which they are placed (see review by Rosenberg and Resh 1982). They are generally used to sample organisms in difficult habitats, to reduce the variability associated with conventional sampling techniques, or to standardize the sampling approach (Hellawell 1978, Lamberti and Resh 1983). Disadvantages include the long periods of time that may be required for populations to reach equilibrium levels, or the selectivity of the substrates for certain organisms, thus inaccurately representing the natural community in some cases. However, in many instances, the advantages of artificial substrates outweigh the disadvantages. In Big Sulphur Creek (BSC), we found that populations on artificial substrates closely represented natural populations within five weeks of placement.

Red clay tiles (15.2 X 7.6 cm) have been used extensively in the benthic sampling program at The Geysers. Tiles are placed on the stream bottom (Fig. III-1) and allowed to be colonized for specified periods of time. Microorganisms are quantitatively sampled from the tile by scraping small areas, whereas all macroinvertebrates are collected from the tile. In one study, tiles were placed in BSC directly upstream and downstream of a natural geothermal tributary, Little Geysers Creek (LGC). After seven weeks' exposure (Table III-1), there were higher abundances of both microorganisms and macroinvertebrates at BSC-downstream.

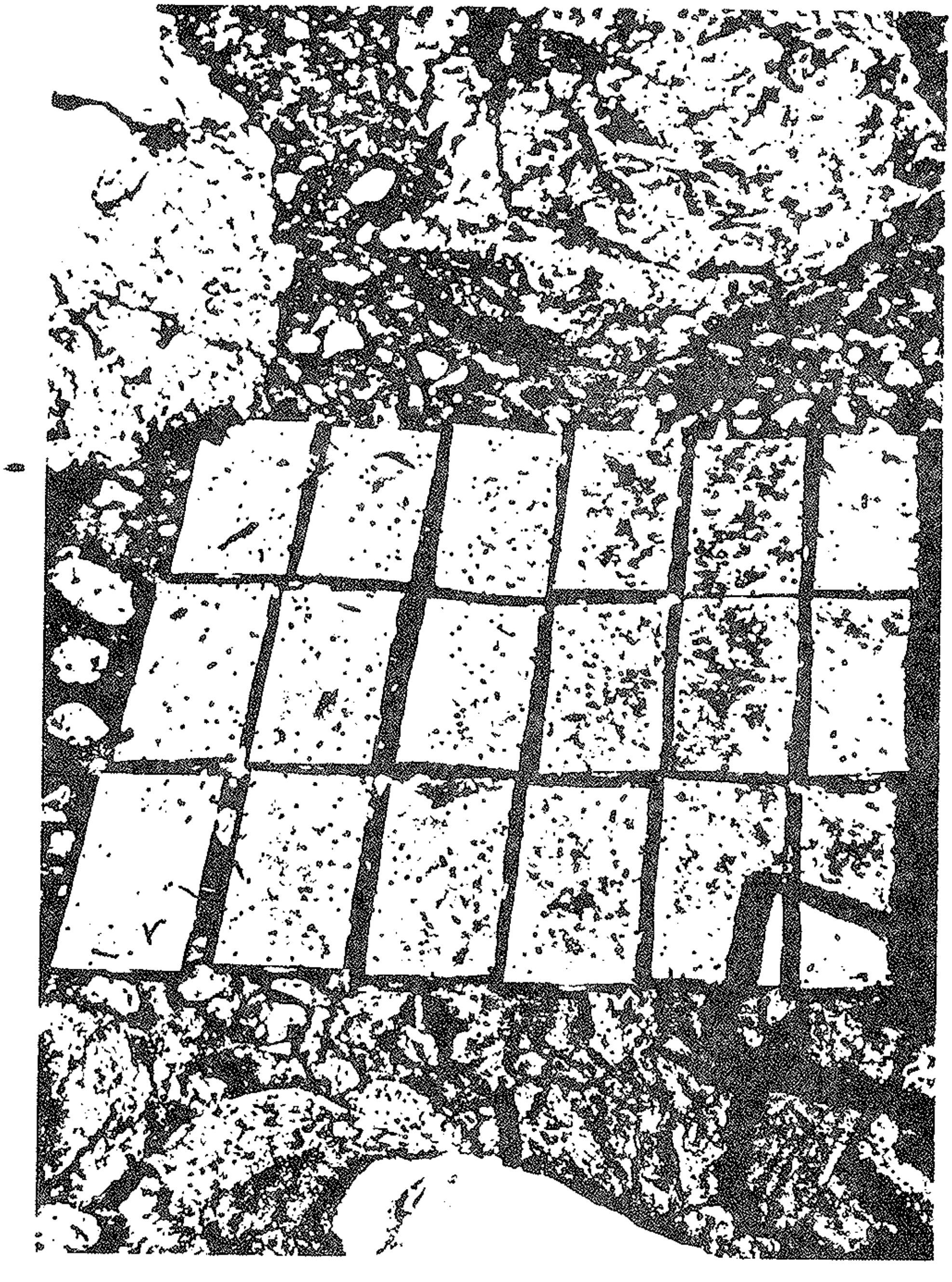


Figure III-1

TABLE III-1

LOCATION	MICROORGANISMS		MACROINVERTEBRATES	
	Bacteria ($X10^8/cm^2$)	Chlorophyll a ($\mu g/cm^2$)	Density ($no/0.01m^2$)	Biomass ($mg/0.01m^2$)
BSC Upstream of LGC	23.0	0.48	194	16.3
BSC Downstream of LGC	2.7	0.03	115	2.0

III-2. HYPORHEIC POT

To examine hyporheic (i.e. subsurface) populations in geothermal and in non-geothermal streams at The Geysers, we used a "hyporheic pot", which was modified from the designs of Coleman and Hynes (1970) and Gilpin and Brusven (1976). Our sampler is a perforated PVC cylinder (length = 35 cm, diameter = 8.9 cm) divided with solid plates into four vertically-oriented sections: one 5-cm surface (225 ml) layer and three consecutive 10-cm sub-surface (450 ml each) layers (Fig. III-2). The pot is buried vertically in the substrate such that the top of the sampler is flush with the natural substrate surface. A nested assembly of interchangeable units allows rapid field processing of the individual depth sections.

As part of a reconnaissance study of Big Sulphur Creek, we determined the time required for the hyporheic pots to reach equilibrium insect densities. A group of pots was buried in the streambed and 1-2 pots were retrieved at 2-week intervals (Table III-2). Following an initial period of high macroinvertebrate densities (e.g. after two weeks), equilibrium for total numbers of individuals was reached after six weeks. Bishop (1973) observed a similar pattern, and attributed the decline in numbers to slow filling of the interstitial spaces within the sampler by silt. The 15-25 cm level had the highest density of sub-surface insects at all times.

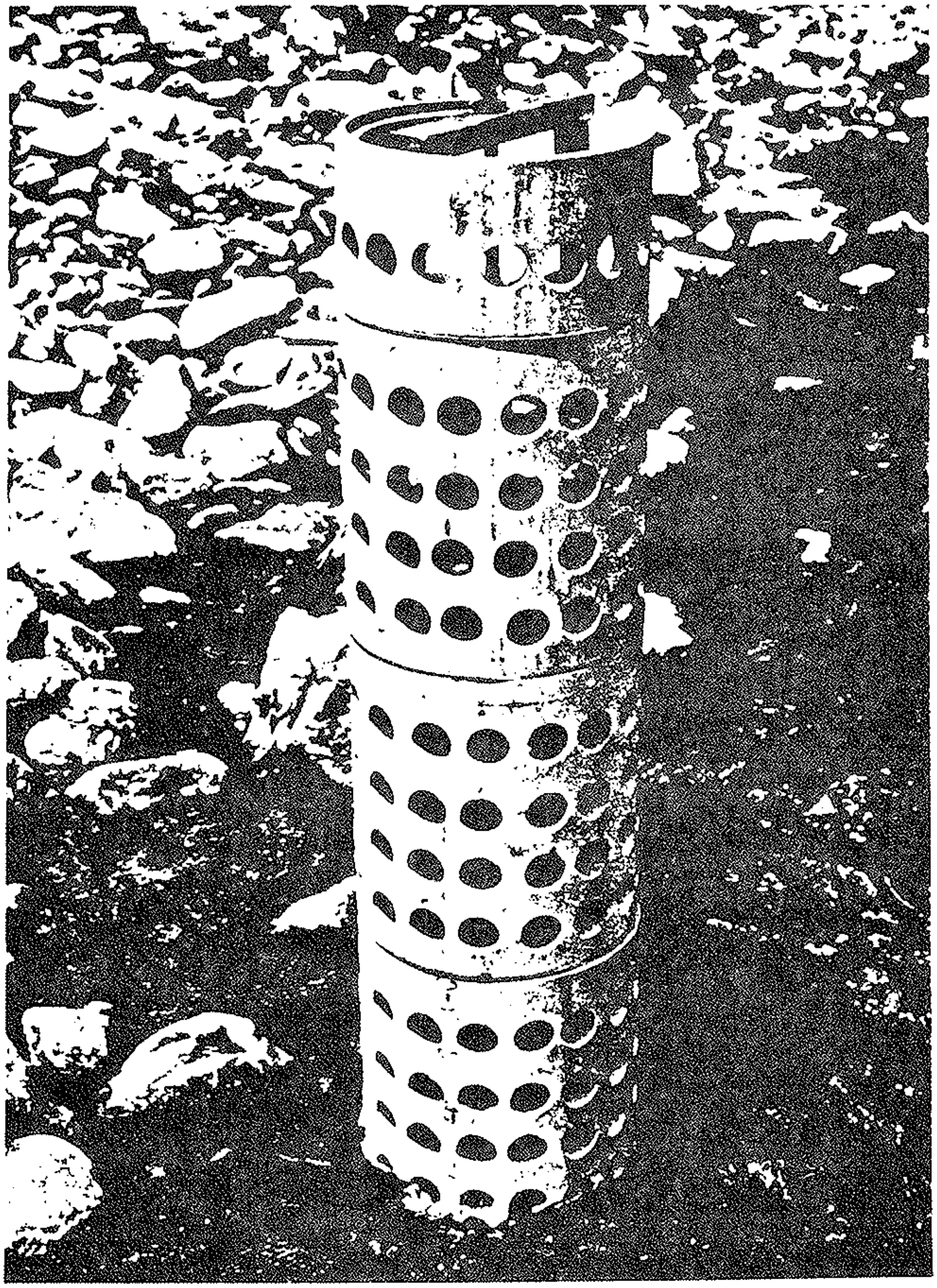


Figure III-2

TABLE III-2

DEPTH STRATUM	$\bar{X}$ INDIVIDUALS/SAMPLE			
	2 wk	4 wk	6 wk	8 wk
Surface	139	11	24	19
5-15 cm	31	8	3	4
15-25 cm	91	9	8	14
25-35 cm	9	3	2	2
All Strata	270	31	37	39

III-3. SUBSTRATE IMPLANT

Stream insect communities can frequently be effectively sampled with artificial substrates that closely mimic natural habitats (Rosenberg and Resh 1982). Substrate implant devices, such as those described by Crossman and Cairns (1974) and Rabeni and Gibbs (1978), can be used in this manner. At The Geysers, we our substrate implants were 5-cm mesh wire baskets (23 X 23 X 15 cm deep) filled with sterilized stream substrate (Fig. III-3). The baskets were buried flush with the stream bottom and allowed to be colonized for a pre-determined period of time. These samplers allowed a unit sample to be taken to 15-cm depth in substrate containing cobbles and boulders that make other means of sampling difficult.

At The Geysers, five substrate implants were placed at each of three sites: 1) in Big Sulphur Creek (BSC) directly upstream of Little Geysers Creek (LGC), a natural geothermal tributary, 2) in BSC directly downstream of LGC, and 3) within LGC. The samplers were allowed to be colonized for eight weeks (Table III-3). The density of benthic insects was highest within LGC, but the number of species was low. In BSC, insect density was about 10X higher at the downstream site than at the upstream site, although there were similar numbers of species at the two sites.

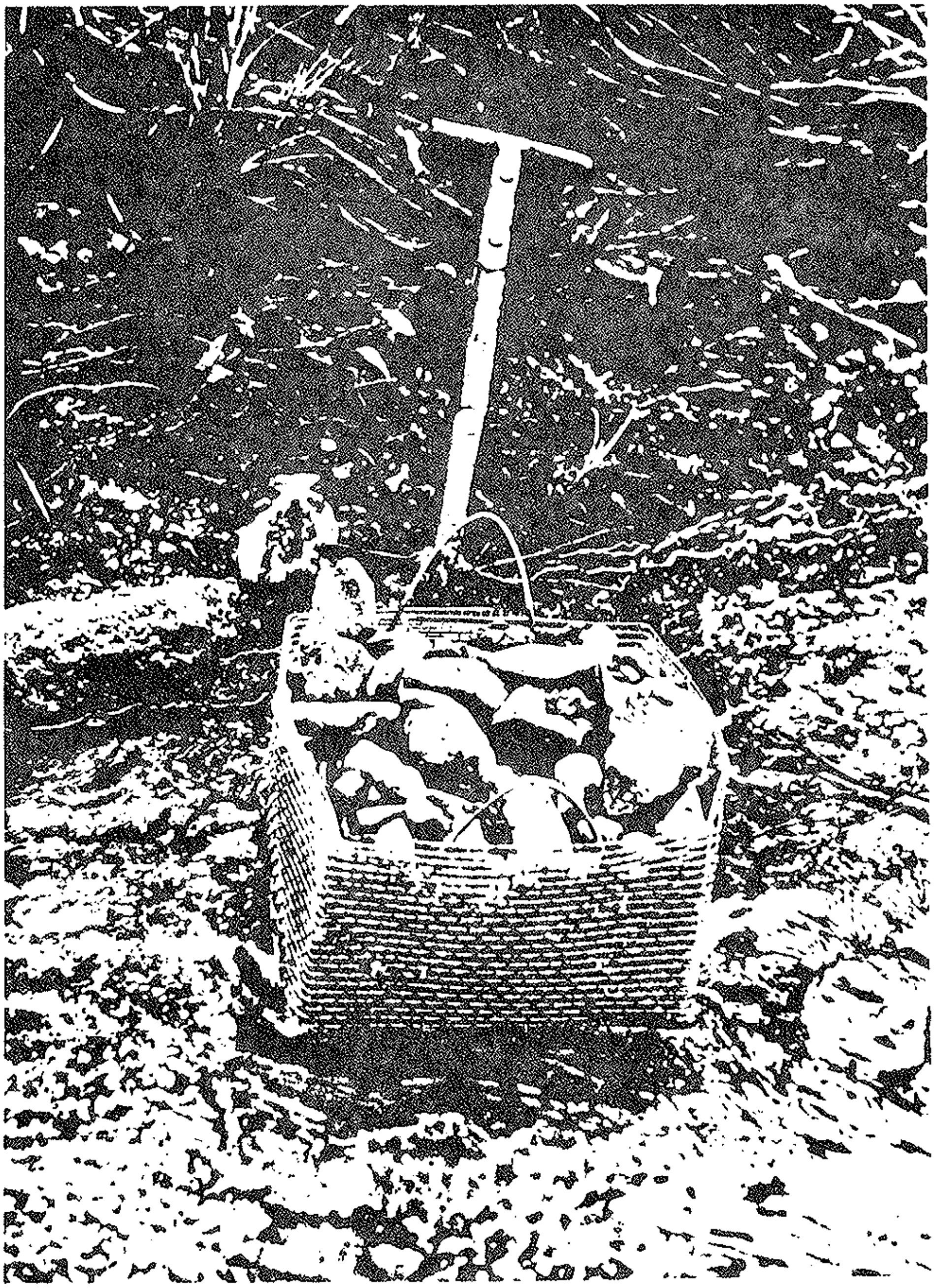


Figure III-3

TABLE III-3

LOCATION	INDIVIDUALS ($no/0.26\ m^2$)	SPECIES ($no/0.26\ m^2$)
BSC Upstream of LGC	1240	36
BSC Downstream of LGC	10,140	38
Within LGC	15,219	13

III-4. COLONIZATION TRAP - OVIPOSITION

Egg-laying by adult female insects is the ultimate source of colonists of aquatic habitats (Hynes 1970). However, proximate sources of insect colonists include drift, upstream movement, and movement through the hyporheic zone. A colonization trap was designed to provide an estimate of that portion of the benthic insect community that colonizes denuded stream substrate due to oviposition by aerial adults (Williams and Hynes 1976). The sampler was a steel tray (30 X 60 X 15 cm deep) open to ovipositing females, and containing 5 cm of sterilized substrate (Fig. III-4). Upstream and downstream ends were fitted with 135-µm mesh nets to allow water to flow through the traps, and styrofoam was used for flotation. One problem with the trap was that the screens would become fouled by algae, which reduced water flow.

One pair of oviposition traps was placed in Big Sulphur Creek (BSC) directly upstream and downstream of Little Geysers Creek (LGC),a natural geothermal tributary, and allowed to be colonized for eight weeks. All insects in the traps were identified and enumerated (Table III-4). There was little difference in the numbers of species at the two sites. However, at the downstream site, there was a two-fold increase in the density of insects, indicating increased oviposition activity in that area.

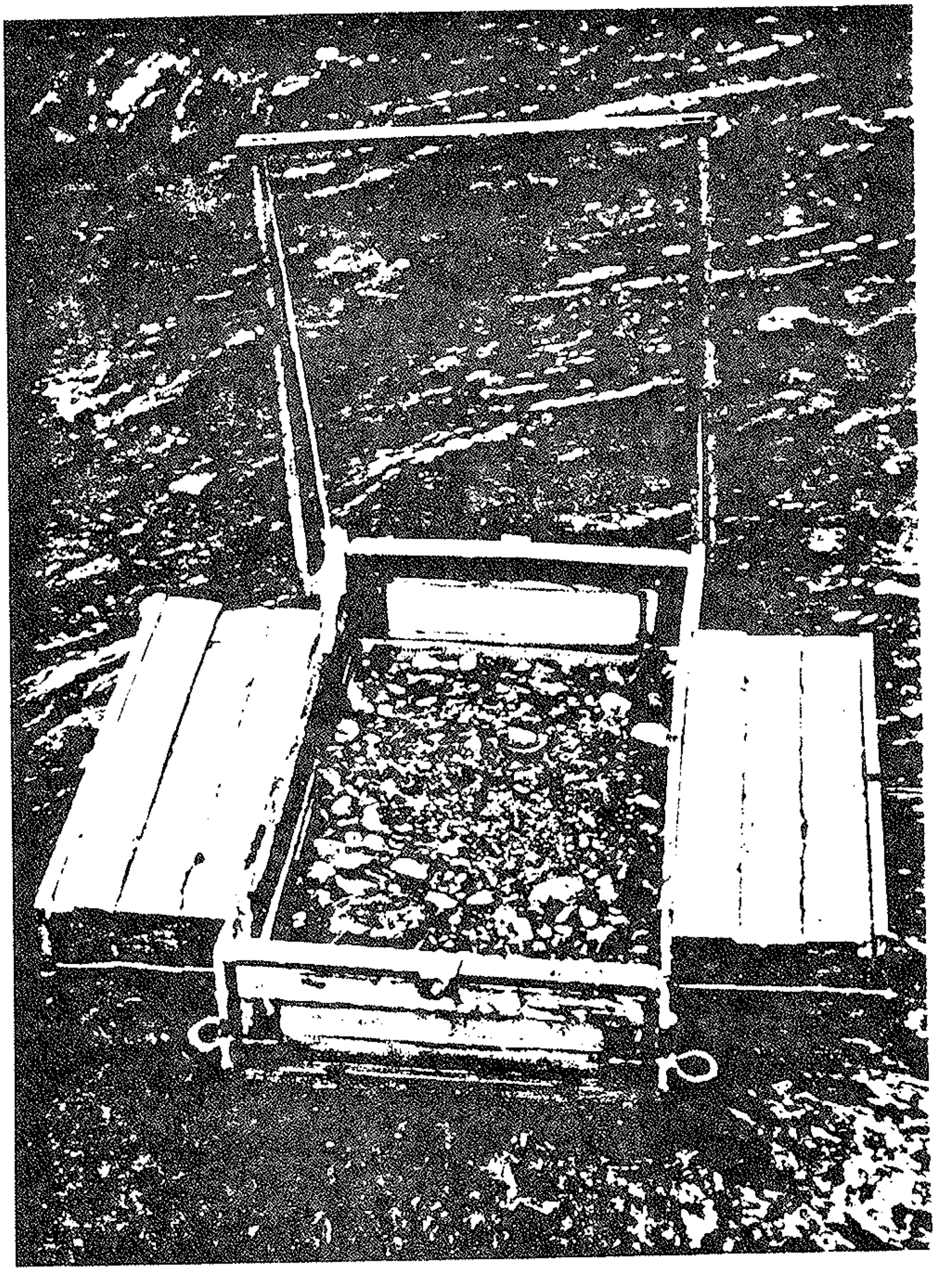


Figure III-4

TABLE III-4

LOCATION	INDIVIDUALS (no/0.36 m^2)	SPECIES (no/0.36 m^2)
BSC Upstream of LGC	652	16
BSC Downstream of LGC	12,948	19

III-5. COLONIZATION TRAP - UPSTREAM MOVEMENT

This device was designed to provide an estimate of that portion of the benthic insect community that colonizes denuded stream substrate by upstream movement (Williams and Hynes 1976). The sampler was a steel and plexiglas box (30 X 30 X 30 cm deep) with solid bottom, sides, and top (Fig. III-5). The downstream end of the trap was open, which allowed entry to insects moving upstream on or through the substrate. A 135-μm mesh net at the upstream end allowed water to flow through but prevented entry by drifting insects. The trap was supplied with 5 cm of sterilized substrate and buried 5 cm into the stream bottom. As with the aerial traps, we observed some fouling of the upstream net, which impeded water flow through the trap.

One pair of upstream-movement traps was placed in Big Sulphur Creek (BSC) directly upstream and downstream of Little Geysers Creek (LGC), and allowed to be colonized for eight weeks. All insects in the traps were identified and enumerated (Table III-5). At the downstream site, there was both a higher density of insects and an increase in the number of species, indicating greater upstream movement in that area.

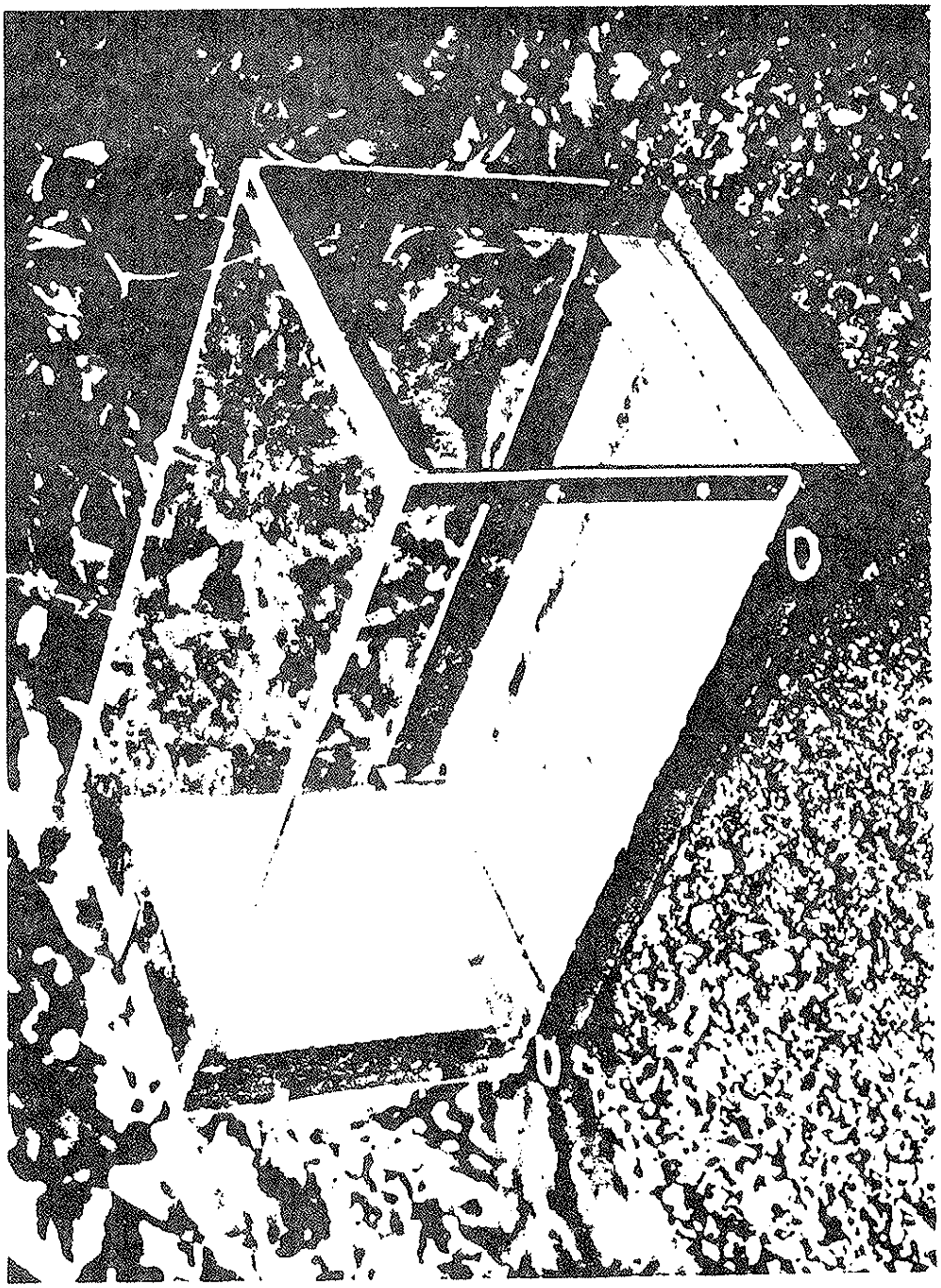


Figure III-5

TAPLE III-5

LOCATION	INDIVIDUALS (no/0.36 m^2)	SPECIES (no/0.36 m^2)
BSC Upstream of LGC	2868	21
BSC Downstream of LGC	7704	26

III-6. COLONIZATION TRAP - DRIFT

This device was designed to provide an estimate of that portion of the benthic insect community that colonizes denuded stream substrate by drift, which is the downstream movement of organisms in the water column (Williams and Hynes 1976). The sampler was a steel and plexiglas box (30 X 60 X 30 cm deep) with solid bottom, sides, and top, and containing 5 cm of sterilized substrate (Fig. III-6). The upstream end was open to allow drifting insects to enter the sampler. A 135-μm mesh drift net was attached to the downstream end to monitor drift. Because of the large surface area of the drift net, reduction of flow due to fouling of the net was not as problematic as with the other types of colonization samplers.

One pair of drift traps was placed in Big Sulphur Creek (BSC) directly upstream and downstream of Little Geysers Creek (LGC), and allowed to be colonized for eight weeks. All insects in the traps were identified and enumerated (Table III-6). At the downstream site, there was a two-fold increase in the density of insects and a 40% increase in the number of species, indicating increased insect drift in that area.

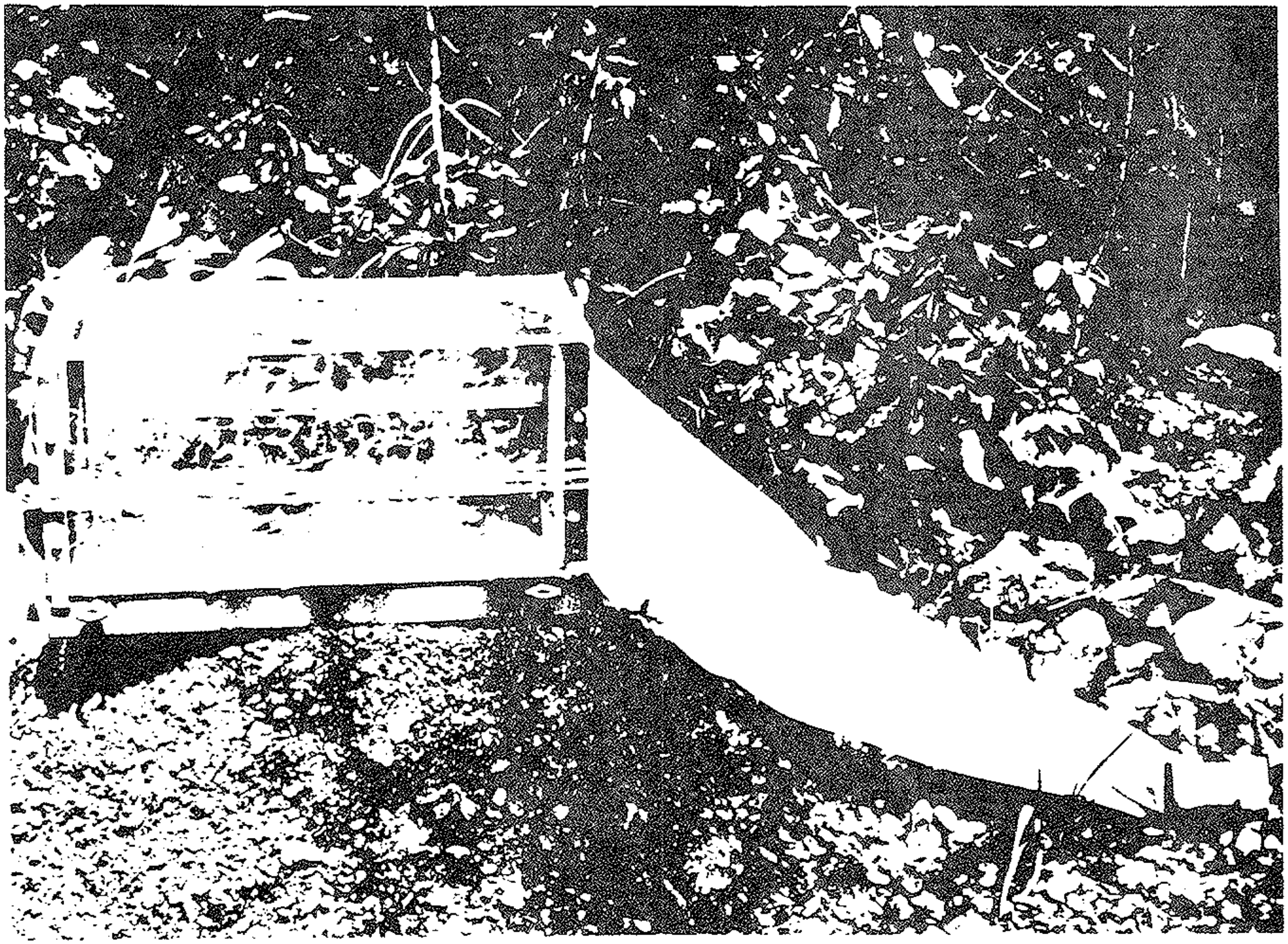


Figure III-6

TABLE III-6

LOCATION	INDIVIDUALS (no/0.36 m^2)	SPECIES (no/0.36 m^2)
BSC Upstream of LGC	3948	26
BSC Downstream of LGC	7662	36

III-7. COLONIZATION TRAP - HYPORHEIC MOVEMENT

This device was designed to provide an estimate of that portion of the benthic insect community that colonizes denuded stream substrate by movement through the interstitial spaces of the hyporheic, i.e. sub-surface, zone (Williams and Hynes 1976). The sampler was a steel and plexiglas box (30 X 60 X 30 cm deep) with solid sides and top, fitted with a 135-μm mesh net at each end (Fig. III-7). The bottom was was a coarse (1 cm mesh) wire screen that allowed entry by insects migrating upwards from the hyporheic zone. The sampler was filled with 5 cm of sterilized substrate and set 5 cm deep into the streambed. As with the aerial trap, fouling of the upstream net caused some reduction of water flow through the trap.

One pair of hyporheic-movement traps was placed in Big Sulphur Creek (BSC) directly upstream and downstream of Little Geysers Creek (LGC), and allowed to be colonized for eight weeks. All insects in the traps were identified and enumerated (Table III-7). At the downstream site, there was over a three-fold increase in the density of insects and a 25% increase in the number of species, indicating increased hyporheic activity in this area.

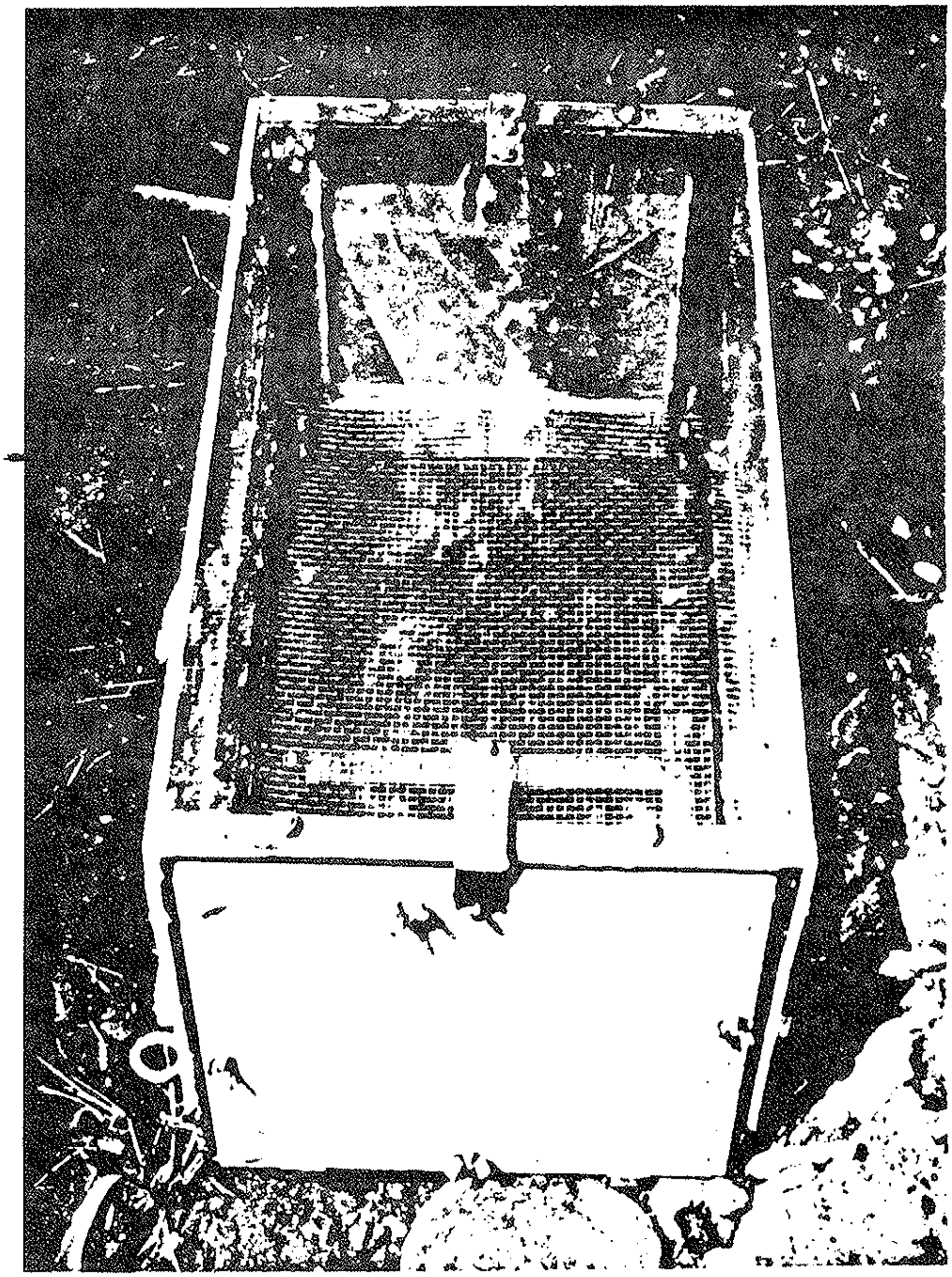


Figure III-7

TABLE III-7

LOCATION	INDIVIDUALS (no/0.36 m^2)	SPECIES (no/0.36 m^2)
BSC Upstream of LGC	1277	20
BSC Downstream of LGC	4589	25

IV-1. VISUAL COUNTS

Visual counts can be used in the field to estimate population densities of specific benthic macroinvertebrates (Lamberti and Resh 1979, Resh 1979a, Hart and Resh 1980, Hart 1981). This technique minimizes disturbance of natural populations and eliminates the need to process samples in the laboratory. However, individuals must be: 1) large enough to be easily counted, 2) restricted in distribution to the substrate surface, and 3) distinguishable from other species. A simple quadrat method can be used to delimit stream bottom areas (Fig. IV-1A) in a random or stratified-random sampling design.

The population density and spatial distribution of the caddisfly *Dicosmoecus gilvipes* (Hagen) in Big Sulphur Creek and in the McCloud River, California, was determined from visual counts of larvae (Lamberti and Resh 1979). For example, in 188 0.093 m^2 quadrats (Fig. IV-1B), *D. gilvipes* had an aggregated distribution, with a mean density of about 7 larvae/0.093 m^2 (SD = 6). This non-disruptive sampling approach permitted repeated sampling of the population without artificially reducing the population size by removal.

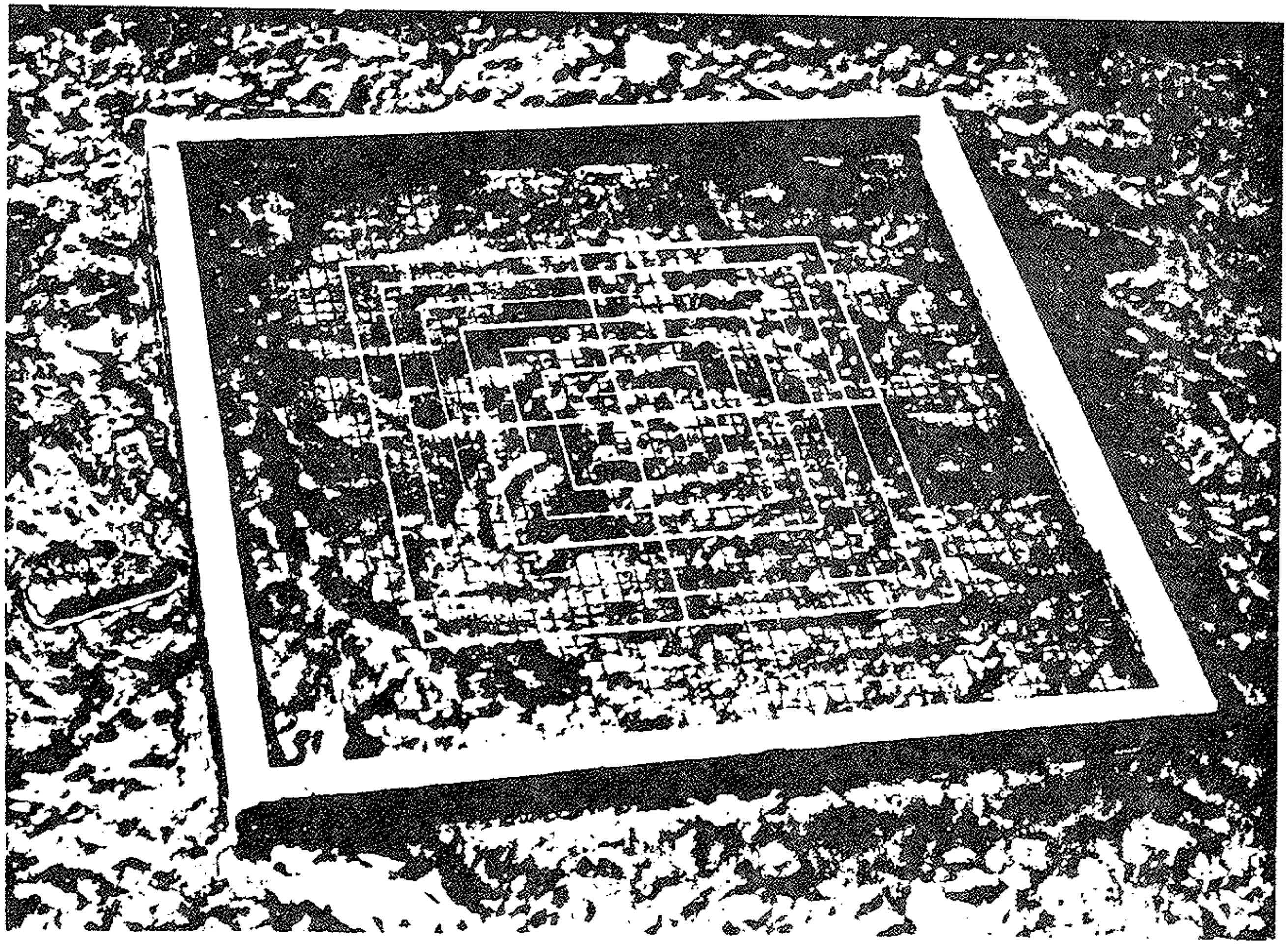
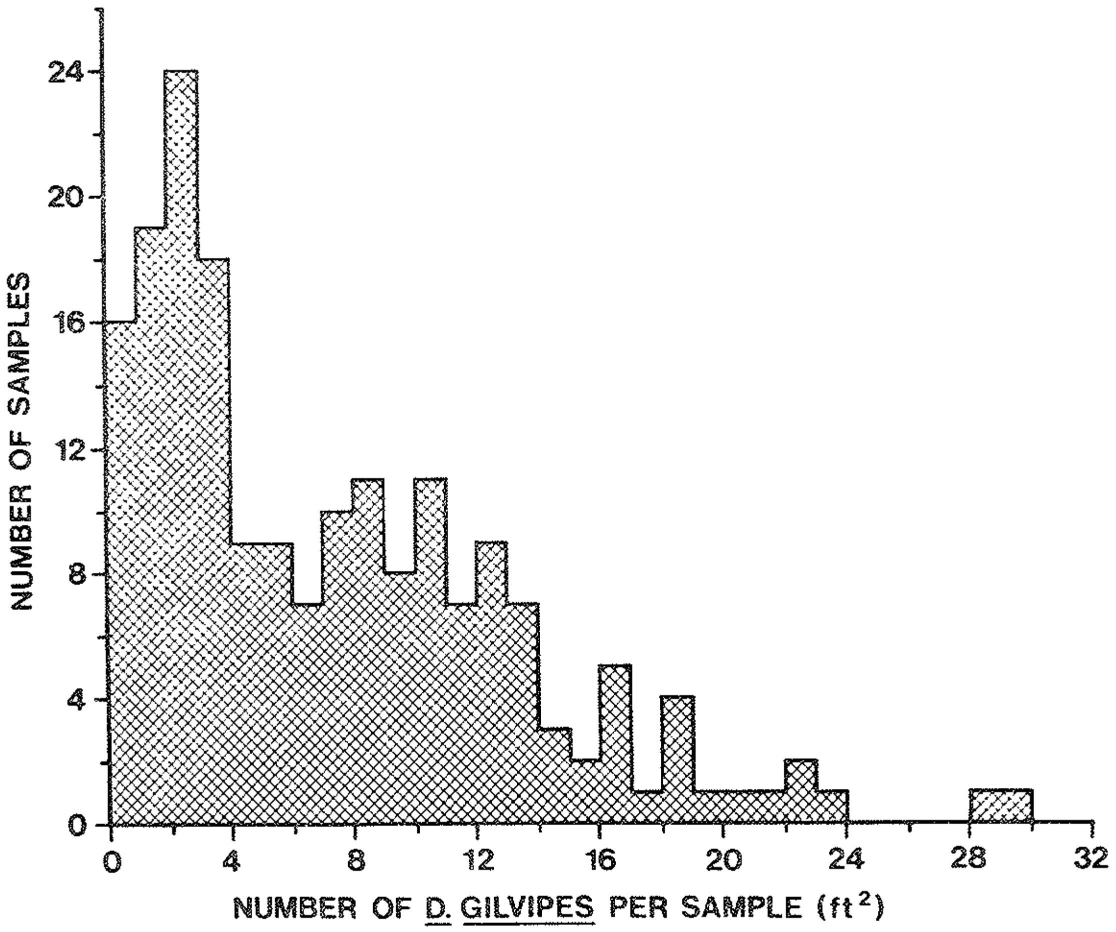


Figure IV-1A



NUMBER OF SAMPLES
24
20
16
12
8
4
0
0
4
8
12
16
20
24
28
32
NUMBER OF D. GILVIPES PER SAMPLE (ft²)

Figure IV-1B

IV-2. PHOTOGRAPHIC METHODS

Photography has been periodically used to study aquatic habitats, including both biotic (e.g. population density; Heywood and Edwards 1962) and abiotic features (e.g. substrate composition; Cummins 1962, 1964). To study benthic populations, two conditions must be met: first, the population must have have a two-dimensional distribution (i.e. no hyporheic component); second, there must be sufficient contrast with the background to permit discrimination of individuals. The use of an artificial substrate can be especially effective in meeting these criteria. The dots on the artificial substrate tile (Fig. IV-2) are larvae of the caddisfly Helicopsyche borealis, an abundant insect in Big Sulphur Creek (BSC) at The Geysers.

Photography was used to determine the population density of H. borealis on artificial substrate tiles in BSC that had different initial standing crops of algae (Table IV-2). Densities were determined by counting the number of larvae on the upper surface of each substrate from black and white photographs or projections of color transparencies. The density of H. borealis was positively correlated with the standing crop of algae. High algal biomass is frequently encountered in geothermally influenced streams at The Geysers. This non-disruptive sampling approach allowed repeated measurements of the population over time without habitat disturbance.

Figure IV-2

TABLE IV-2

CHLOROPHYLL <u>A</u> (initial $\mu g/cm^2$)	$\overline{X}$ <u>HELICOPSYCHE</u>/0.01 M^2 AFTER FOUR EXPOSURES			
	2 h	24 h	7 d	15 d
0	2	8	24	59
3	47	65	37	65
15	67	176	58	81

IV-3. PUPAL CLUMP COUNTS

Population densities can be estimated indirectly by examining the structures made by aquatic insects. For example, caddisflies (Trichoptera) construct a pupal case and many species aggregate into dense pupal clumps prior to adult emergence (Waters and Resh 1979, Resh et al. 1981). Direct counts of these pupal cases can yield estimates of population densities (Otto 1976, Southwood 1978). Such a census of adult emergence potential can be used to determine short- and long-term trends in the population dynamics of a species.

A useful feature of the biology of the caddisfly _Gumaga nigricula_ is its formation of extensive pupal aggregations, which are frequently located along the stream margin and are thus easy to find (Fig. IV-3A). We made counts of empty pupal cases in 69 different clumps along a 100 m reach of Big Sulphur Creek shoreline, and the clump size varied from 3 to 1,410 individuals (Fig. IV-3B). However, in future uses of this technique, caution must be exercised to make sure that the counts do not include cases from previous years. For example, we have observed that empty pupal cases in well protected situations are not always removed by high water during the following winter, but signs of ageing in year-old cases can be detected with experience.

Figure IV-3A

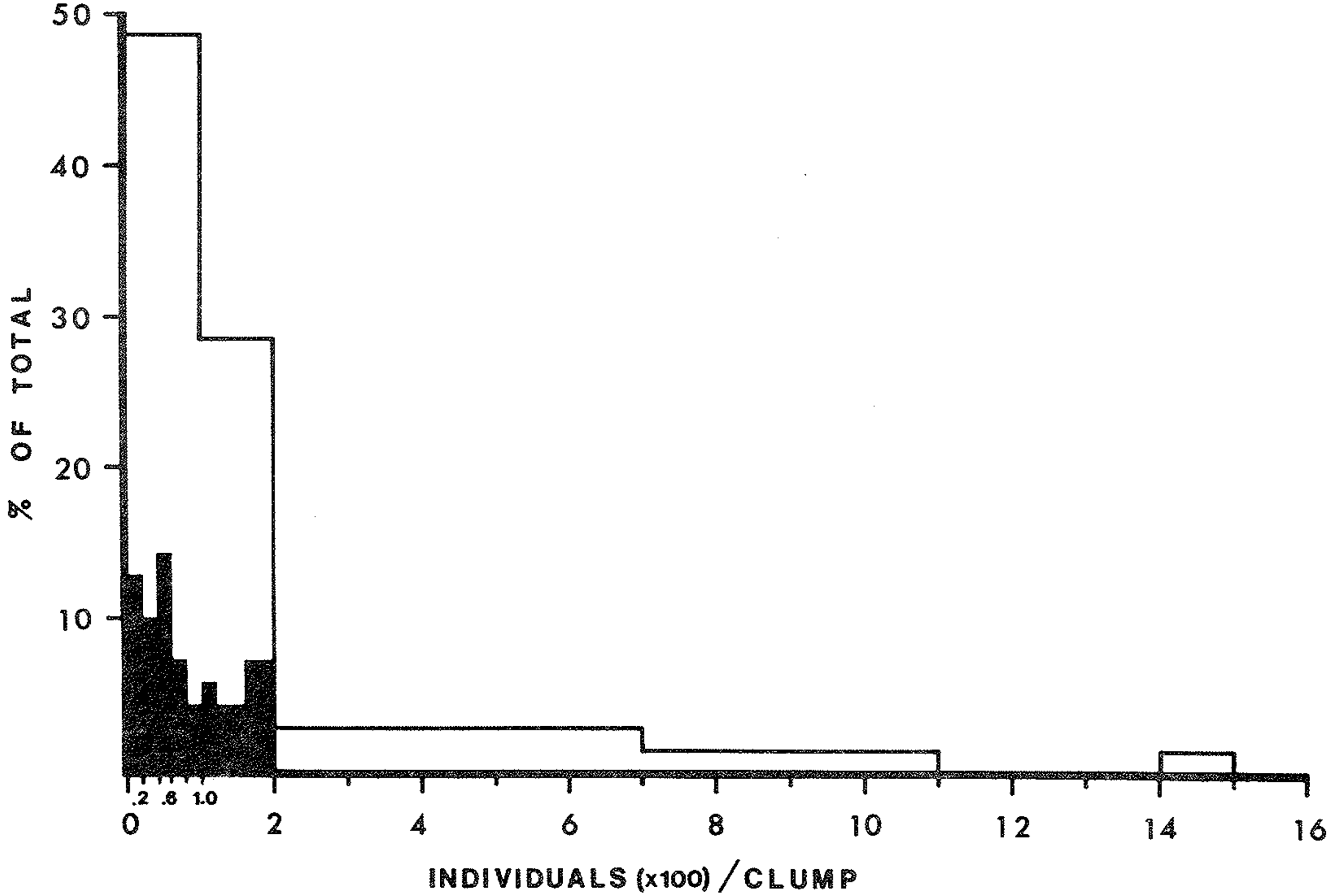

50
40
30
20
10
% OF TOTAL
.2
.6
1.0
0
2
4
6
8
10
12
14
16
INDIVIDUALS (x100) / CLUMP

Figure IV-3B

V-1. PAN TRAP

Pan traps are non-attractive devices that capture adult insects in liquids (e.g. Grigarick 1959, Kuusela and Pulkkien 1978), and are sometimes known as water traps (Southwood 1978). We have produced a model that is suitable for use in and along streams during the dry season. Although pan traps are not quantitative samplers, they probably sample in relative proportion to the abundances present in nature, and may be used to make qualitative comparisons of taxa in different habitats. Our design is composed of a single-post metal frame holding a 28 x 40 cm aluminum roaster pan (Fig. V-1). When filled with a water and ethylene-glycol mixture, the pan captures and preserves adult insects for a period of one to two weeks.

Pan traps were used to compare caddisfly (Trichoptera) species composition and adult flight periods from May - October 1979 in two contrasting geothermal basins, Big Sulphur Creek (BSC) and Big Canyon Creek (BCC). The BSC basin is a steam-dominated geothermal system that has many hot springs and fumeroles. In contrast, the BCC drainage overlays a hot-water geothermal system that makes few direct thermal contributions to the stream. Although the two systems share many families and genera of caddisflies (Table V-1), they share relatively few species. The pan traps used in our study were best suited for capturing Trichoptera, Ephemeroptera, and Diptera, but were less efficient for trapping Odonata, Hemiptera, and Plecoptera.

Figure V-1

TABLE V-1

	TOTAL NUMBER		
TRICHOPTERA	BSC	BCC	In Common
Families	9	10	7
Genera	15	14	10
Species	19	15	6

V-2. PHEROMONE TRAP

Pheromones are external substances that are produced by one organism and cause a reaction in other organisms of the same species (Karlson and Butenandt 1959). Although it has been known since the early 1800's that insects produce these "odors", pheromone sampling methods are relatively new and most widely used in agriculture (Carde 1976, Shorey and McKelvey 1977). Only a few examples of pheromone-producing organs have been described in aquatic insects (e.g. Moretti and Bicchierai 1981). This mode of communication has been only rarely incorporated in studies of population dynamics or taxonomy. We discovered a pheromone system in the caddisfly genus *Gumaga* (Sericostomatidae), of which G. *nigricula* is an abundant species at The Geysers (Wood and Resh, in press). Since precise identification of species has been shown to be important in environmental biomonitoring efforts (Resh and Unzicker 1975), pheromone traps were used in a taxonomic study of *Gumaga*.

We used commercially manufactured traps (Pherocon 1C; Zoecon Corporation) with living, virgin *G. griseola* and *G. nigricula* females as bait, and empty traps as controls (Fig. V-2). The traps were placed overnight in *G. griseola* habitat and the sex, number, and species identity of captured caddisflies were recorded (Table V-2). *G. griseola* males were only attracted to conspecific females. This attraction is chemically mediated by a pheromone (Wood and Resh, in press). The use of pheromone traps in population surveys may be preferable to light-trap methods, because the attractant is species-specific and does not appear to alter normal behavior (Carde 1976).

Figure V-2

TABLE V-2

TREATMENT	TOTAL *G. GRISEOLA* MALES CAPTURED (1982)			
	VI-16	VI-17	VI-20	VI-23
Control	0	0	1	0
G. griseola ♀	14	62	122	71
G. nigricula ♀	0	1	0	0

V-3. ULTRAVIOLET LIGHT TRAP

The ultraviolet light trap is a commonly used device for qualitative sampling of both aquatic and terrestrial insects populations (Fig. V-3A). The applications and limitations of this device have been discussed by Southwood (1978). Many species of aquatic insects are attracted to ultraviolet light; such collections can be used for survey, distribution, and taxomonic purposes. Two disadvantages of light traps are that they attract and capture insects by disrupting their normal nocturnal behavior, and different species are not equally attracted to light. Consequently, trap catches are of little value for comparative studies unless conducted over several seasons. In addition, many aquatic insects do not fly to light when the air temperature falls below 20°C. Light traps are most effective when captures can be compared to other adult sampling methods (e.g. sweeping, pheromone traps, or pan traps).

We used ultraviolet light traps at The Geysers to survey the adult insect fauna, and to verify species identifications of immature stages from Big Sulphur Creek. Light traps, in conjunction with pan traps, were also used to determine the full extent of the flight period of the caddisfly _Gumaga_ _nigricula_ (Resh et al. 1981). Light trap data from the McCloud River, California, for the caddisfly _Hydropsyche_ _oslari_ Banks, a species that is also common at The Geysers, demonstrate the relationship between air temperature and trap capture (Resh and

Sorg 1978). The number of individuals of _H_. _oslari_ captured was positively correlated with the 24-h maximum and minimum temperatures (Fig. V-3B). Ultraviolet light trap sampling programs should incorporate both temperature and wind velocity measurements to ensure more accurate interpretation of results.

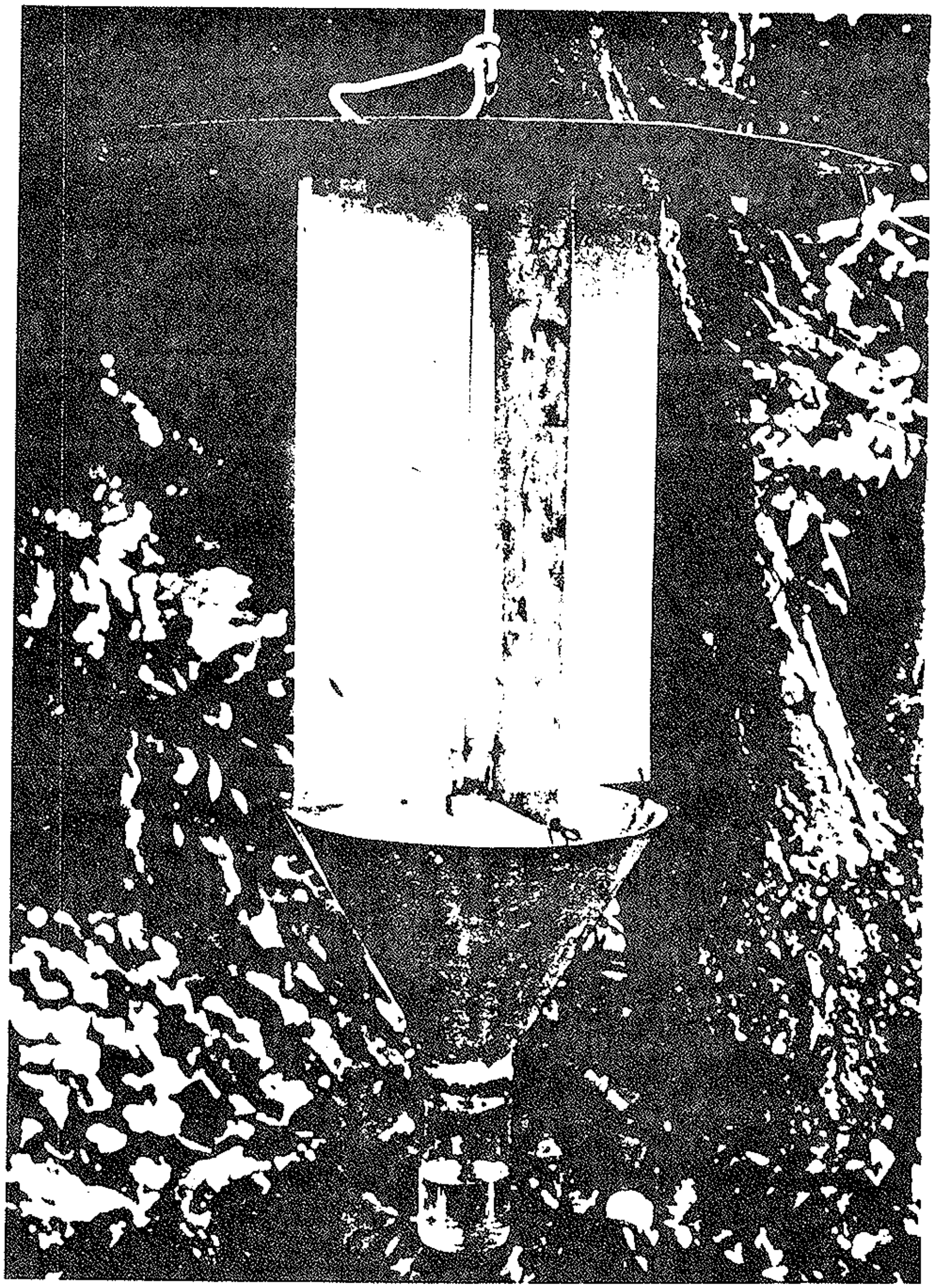
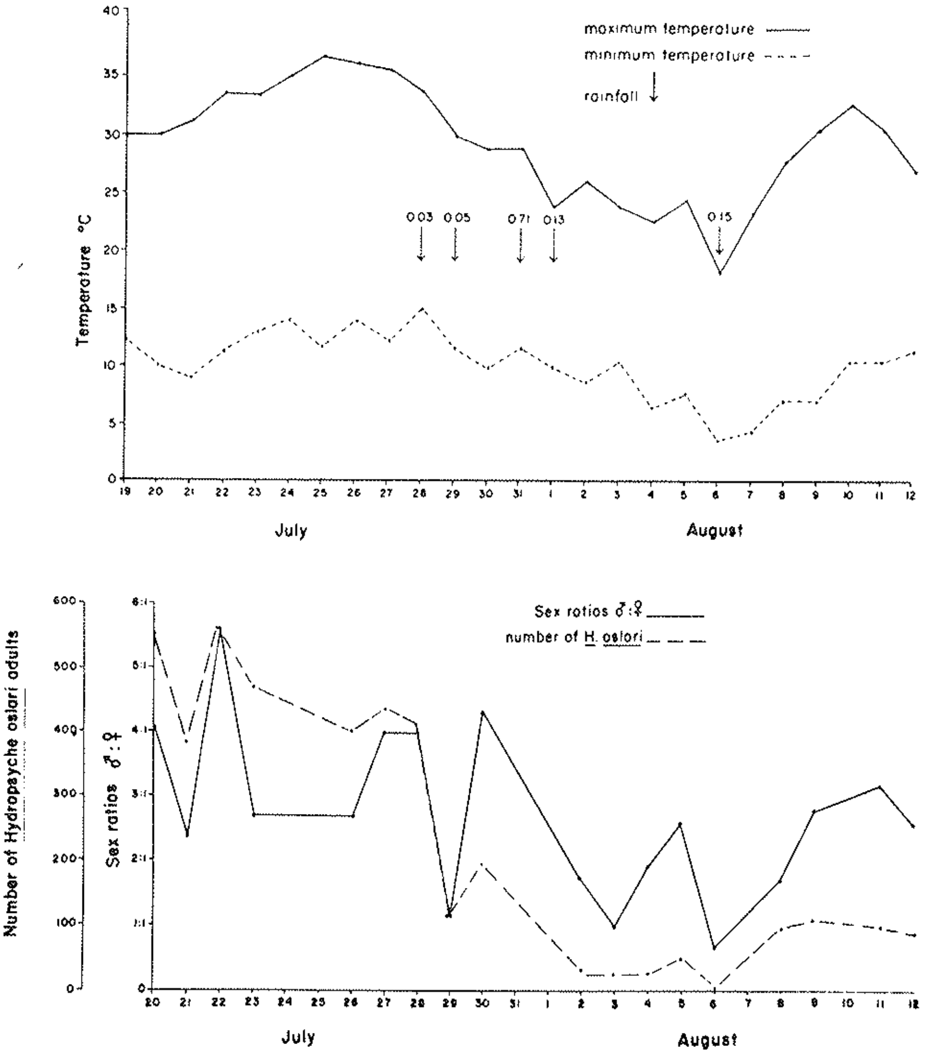


Figure V-3A



40
35
30
25
20
15
10
5
0
Temperature °C
maximum temperature
minimum temperature
rainfall
0.03
0.05
0.71
0.13
0.15
19
20
21
22
23
24
25
26
27
28
29
30
31
1
2
3
4
5
6
7
8
9
10
11
12
July
August
600
500
400
300
200
100
0
Number of Hydropsyche oslari adults
6:1
5:1
4:1
3:1
2:1
1:1
0
Sex ratios ♂:♀
Sex ratios ♂:♀
number of H. oslari
20
21
22
23
24
25
26
27
28
29
30
31
1
2
3
4
5
6
7
8
9
10
11
12
July
August

Figure V-3B

V-4. EMERGENCE TRAP

Sampling designs for aquatic insect studies pose unique problems since immature life stages are aquatic and adults are often aerial. Multi-stage sampling methods are often required to solve these problems. One adult sampling method implemented during studies at The Geysers was found to be inadequate in that setting.

Emergence traps, in contrast to the other adult collection methods described, generally give a quantitative measure of the sampled population (Southwood 1978). Emergence traps have been used in many types of ecological studies, including production dynamics (Illies 1975) and environmental impact asessment (Rosenberg et al. 1981). We developed a small emergence trap for sampling adults that emerge from individual clumps of caddisfly pupae (Fig. V-4; see also Section IV-3). The traps were based on a design used for sampling emerging soil insects (Turnock 1957). A one gallon (3.8 l) plastic jar, which was coated on the inside with adhesive, was mounted on a screen-covered wire frame and placed over a pupal clump. However, we found that emerging caddisflies tended to avoid the trap by swimming under the wire skirt. A fully-adjustable trap base having a skirt that can extend to the substrate may reduce this source of sampling error.

Figure V-4

VI-1. STREAM MICROCOSMS

At The Geysers, geothermal fluids from natural hot springs and from geothermal energy development activities have created unique geothermal stream habitats (Resh et al. 1981). Such geotheral fluids have two components, high temperature and chemical substances, that affect the abundance and diversity of aquatic organisms (Brock 1970, 1978). A field-based, stream microcosm system (Fig. VI-1) was developed to experimentally separate those thermal and chemical components, in order to assess their independent effects on benthic organisms in Big Sulphur Creek (Lamberti and Resh, in review). The resulting information can be used to refine mitigation methods used to protect aquatic habitats during geothermal energy development.

Microorganisms and macroinvertebrates were quantitatively sampled from each of four microcosms after a 35-d exposure period (Table VI-1). When compared to a *control*, experimental heating of non-geothermal water (*thermal* treatment) increased microbial biomass (algae and bacteria), but decreased the number of macroinvertebrates. When compared to geothermal water (*thermal plus chemical*), experimental cooling of those fluids (*chemical* treatment) decreased the productivity of microorganisms, but increased the number of macroinvertebrates. At The Geysers, the thermal component of geothermal fluids has more influence than the chemical component in determining the structure and productivity of the benthic community.

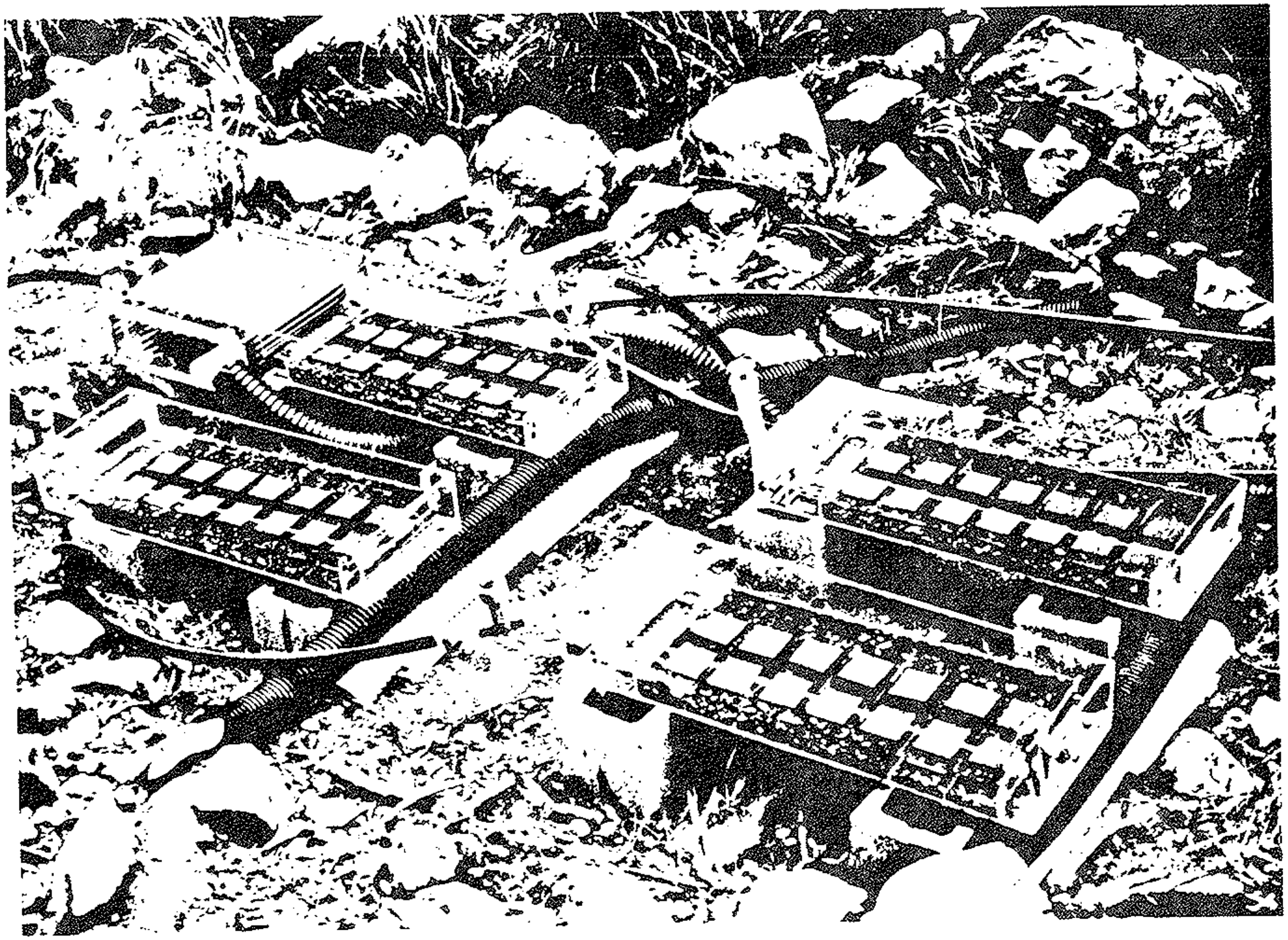


Figure VI-1

TABLE VI-1

	MICROORGANISMS		MACROINVERTEBRATES		
	Bacteria ($X10^8/cm^2$)	Chlorophyll <u>a</u> ($\mu g/cm^2$)	Density ($no/0.2m^2$)	Biomass ($mg/0.2m^2$)	Species ($no/o.2m^2$)
CONTROL	0.53	0.22	4628	211	45
THERMAL	1.17	8.75	3559	231	44
CHEMICAL	4.34	28.55	5678	215	7
THERMAL+ CHEMICAL	4.99	20.61	85	26	3

VI-2. HEAT SHOCK FIELD EXPERIMENT

Naturally heated waters, such as those found at The Geysers, present a unique opportunity to study biological processes (Brock 1970,1975). We designed a new type of field experiment to determine the upper lethal temperature thresholds for three insect species in the Big Sulphur Creek (BSC) drainage. This heat shock experiment simulates the effect of the lethal temperatures that seasonally occur in geothermal tributaries to BSC. It also mimics the effects of artificially heated effluents on drifting aquatic organisms. The results from this experiment can be used in setting thermal limits for effluents from electrical power projects.

The experimental protocol was the same for all three experimental organisms, the mayfly Centroptilum sp. and the caddisflies Helicopsyche borealis (Hagen) and Gumaga nigricula (MacLachlan). Ten animals were placed into each of 42 5-cm-diameter PVC cells, which were arranged in a 6 X 7 time-temperature matrix. The cells were held in a floating rack anchored in the stream (Fig. VI-2). They were quickly removed and transferred to one of the temperature baths on shore for the appropriate time interval. The experiment was repeated 3 times and mortality was determined after 24 h. We present the results of the test with H. borealis (Table VI-2). The time-temperature data, together with field observations, indicate that in BSC, H. borealis larvae are living near the species' lethal thermal threshold of about 39°C.

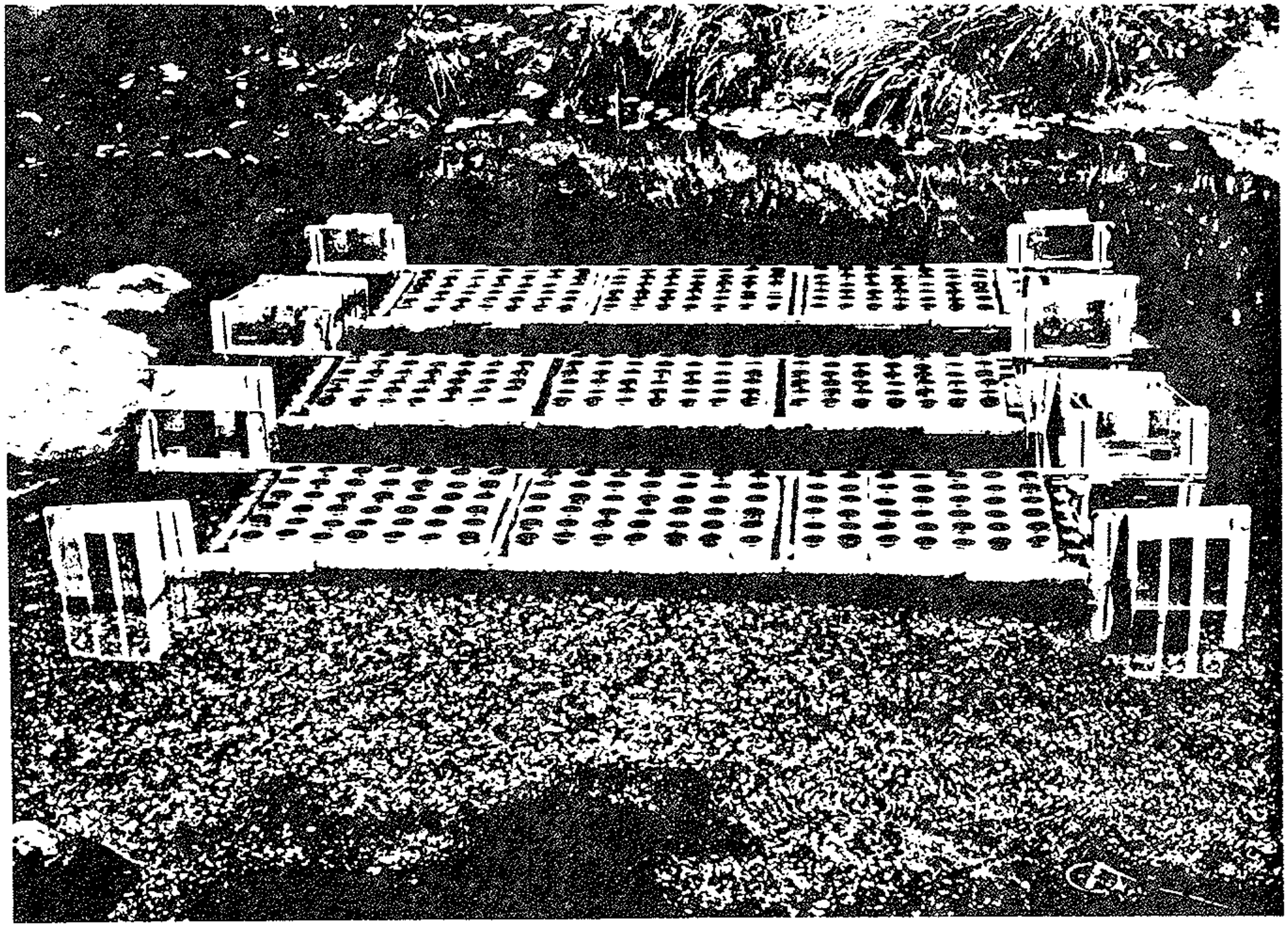


Figure VI-2

TABLE VI-2

TEMPERATURE	$\overline{X}$ % 24-H MORTALITY/EXPOSURE					
(°C)	5	10	15	20	30	60 min
28	3	0	0	0	0	3
33	0	0	0	0	0	0
36	0	0	0	0	0	0
39	0	3	0	6	0	56.7
41	3	76.7	83.3	100	100	100
43	100	100	100	100	100	100
45	100	100	100	100	100	100

VI-3. PRIMARY PRODUCTION

Primary productivity of periphyton can be determined by measuring the oxygen produced during incubation in light (photosynthesis) and dark (respiration) chambers (Fig. VI-3; Vollenweider 1969). When evaluating oxygen production by stream periphyton, the contents of the chambers should be stirred in some manner to simulate flowing water. In Big Sulphur Creek (BSC), the contents of 2.75 l plexiglas chambers were mixed using magnetic stirring bars and external forced-air stirrers (Lamberti and Resh 1983). The difference between light and dark oxygen concentrations following incubation is the gross photosynthetic activity of the periphyton.

Nine replicate 1 h incubations (Table VI-3) were conducted each for: 1) periphyton that was grazed by insect herbivores (as in cool sections of BSC), and 2) periphyton that was not grazed by insect herbivores (as might occur in geothermal streams). Where herbivores were not present, the periphyton produced more oxygen, indicating higher primary productivity in these habitats.

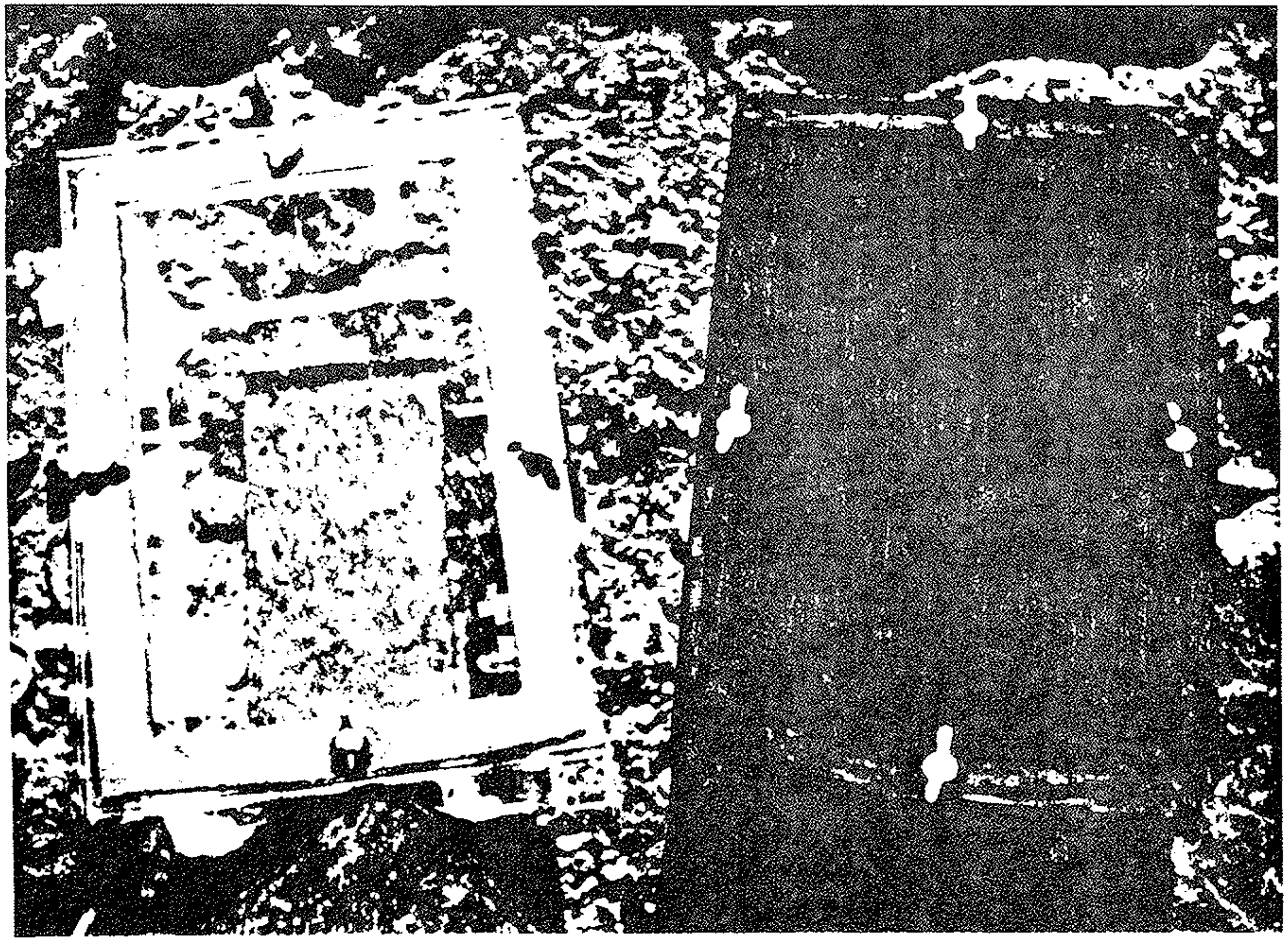


Figure VI-3

TABLE VI-3

	DISSOLVED OXYGEN CONCENTRATION		
	Light (mg/l)	Dark (mg/l)	Gross Photosynthesis (mg/l) = ($\mu g \cdot cm^{-2} \cdot h^{-1}$)
HERBIVORES	10.4	9.7	0.7 = 13.1
NO HERBIVORES	10.9	9.6	1.3 = 24.3

VII-1. CALIBRATION OF ARTIFICIAL SUBSTRATES

Artificial substrates have been extensively used in stream benthic studies. However, a frequent disadvantage is that the artificial substrates are not representative of natural substrates, and consequently do not accurately measure the effects of pollution (Rosenberg and Resh 1982). The accuracy of artificial substrates can be determined by comparing their colonization dynamics with those of natural substrates, such as stream rocks. Because artificial substrates were an integral part of the benthic sampling program at The Geysers, we conducted such a comparison in Big Sulphur Creek (BSC).

Artificial substrates (red clay tiles) were calibrated against natural steam rocks (Fig. VII-1). Both types were sterilized, placed in BSC at the same time, and sampled at one-month intervals. After two months, natural and artificial substrates had very similar benthic communities (Table VII-1), such as in abundances of bacteria, algae, and macroinvertebrates. Based on this information, tiles have been used to sample benthic organisms in studies of geothermal effluents at The Geysers.

Figure VII-1

TABLE VII-1

SUBSTRATE	MICROORGANISMS		MACROINVERTEBRATES	
	Bacteria ($X 10^8/cm^2$)	Chlorophyll *a* ($\mu g/cm^2$)	Individuals ($no/0.01m^2$)	Species ($no/0.01m^2$)
Artificial	8.9	3.5	250	13
Natural	6.9	3.8	307	15

VII-2. COMPUTER-AIDED DISPERSION ANALYSIS

Computer graphics can be used to determine the spatial distributions of benthic macroinvertebrate populations from photographs. One technique to analyse dispersion, nearest-neighbor analysis (Clark and Evans 1954), requires that distances be measured between randomly-selected individuals and their nearest neighbors. These measurements can be obtained by projecting color transparencies of populations onto a computer graphics tablet and using electronic digitation to compute the distances between individuals (Fig. VII-2).

The spatial distribution patterns of *Helicopsyche borealis*, an abundant caddifly in Big Sulphur Creek, were determined on artificial substrates that had different standing crops of algae (Table VII-2). The index *R* varies from 0-2.15, where $R=1$ indicates a random distribution, $R<1$ indicates an aggregated distribution, and $R>1$ denotes a uniform distribution. *H. borealis* larvae were aggregated where high standing crops of periphyton were present, but were randomly distributed on low standing crops of periphyton. Therefore, photography can be effectively coupled with computer techniques to accurately measure population parameters of indicator organisms at The Geysers and in other settings.

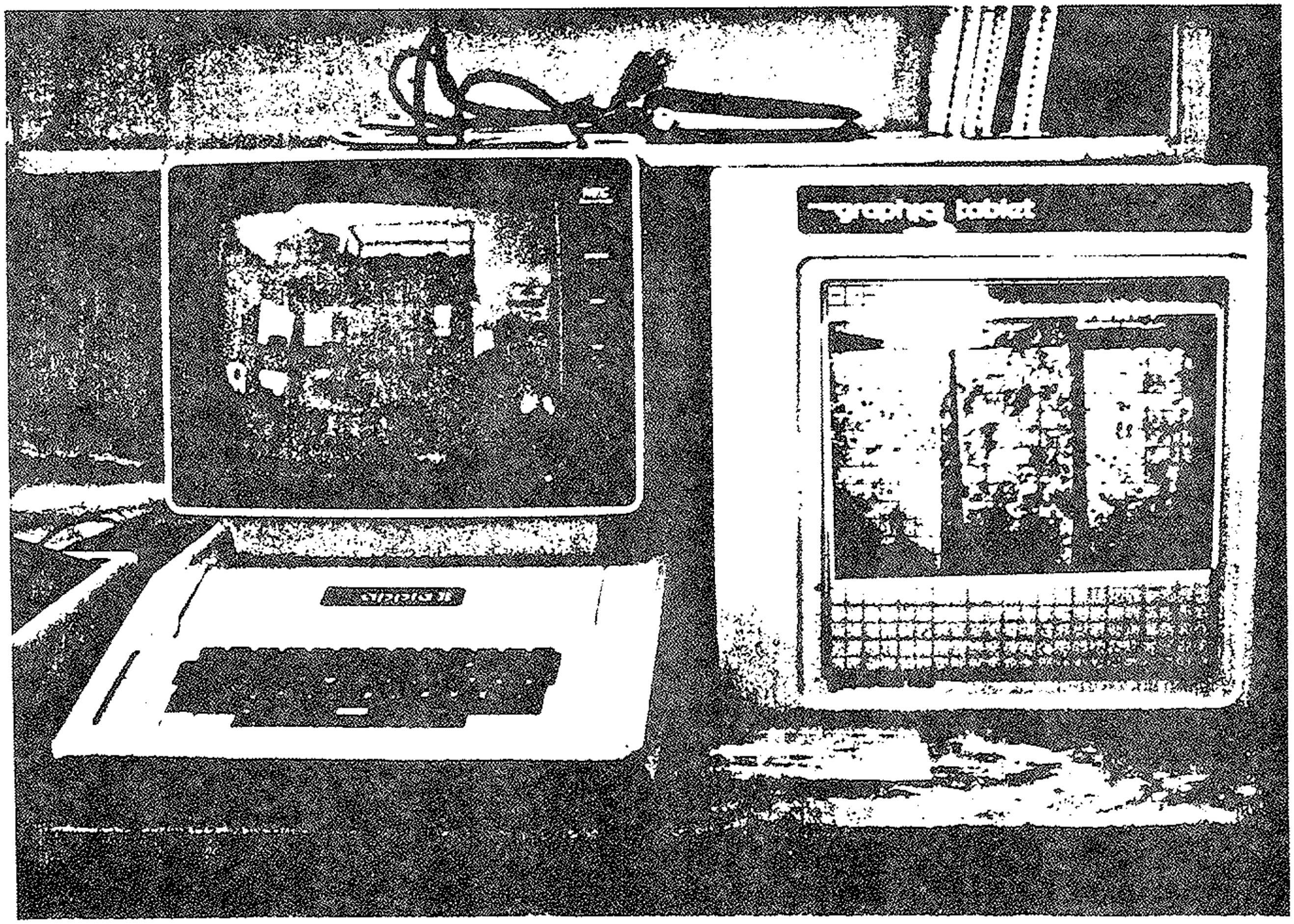


Figure VII-2

TABLE VII-2

	STANDING CROP OF ALGAE (chlorophyll *a*)		
	0.34 μg/cm^2	2.98 μg/cm^2	15.07 μg/cm^2
R	1.15	0.41	0.37
p	NS	<0.01	<0.01
Dispersion	Random	Aggregated	Aggregated

p = statistical significance of the difference between the observed distribution and the expected (random) distribution;

NS = no significant difference

VII-3. ELUTRIATION

Elutriation of benthic samples can be used to separate macroinvertebrates from mineral substrates. Air is bubbled into a substrate-water mixture held in a vertical column (Fig. VII-3A); this agitation suspends organic materials for subsequent decantation (see designs of Lauff et al. 1961, Stewart 1975, Kingsbury and Beveridge 1977). Elutriation reduces sample-processing time by eliminating meticulous hand-picking of specimens. However, certain heavy organisms such as cased caddisflies may not be recovered by elutriation. This technique works best on samples with low organic content, because extraneous organic matter (e.g. algae, detritus) will also be removed and require additional sorting time.

Sixty-one Surber (0.093 m^2) samples obtained from a variety of substrate types in Big Sulphur Creek were elutriated for 30 min/sample (Fig. VII-3B). Greater than 99% of all macroinvertebrates were removed in one-third of the samples, >95% in four-fifths of the samples, and >90% in over nine-tenths of the samples. Most of the unrecovered organisms were caddisflies, such as <u>Helicopsyche</u> <u>borealis</u>, that have compact mineral cases.

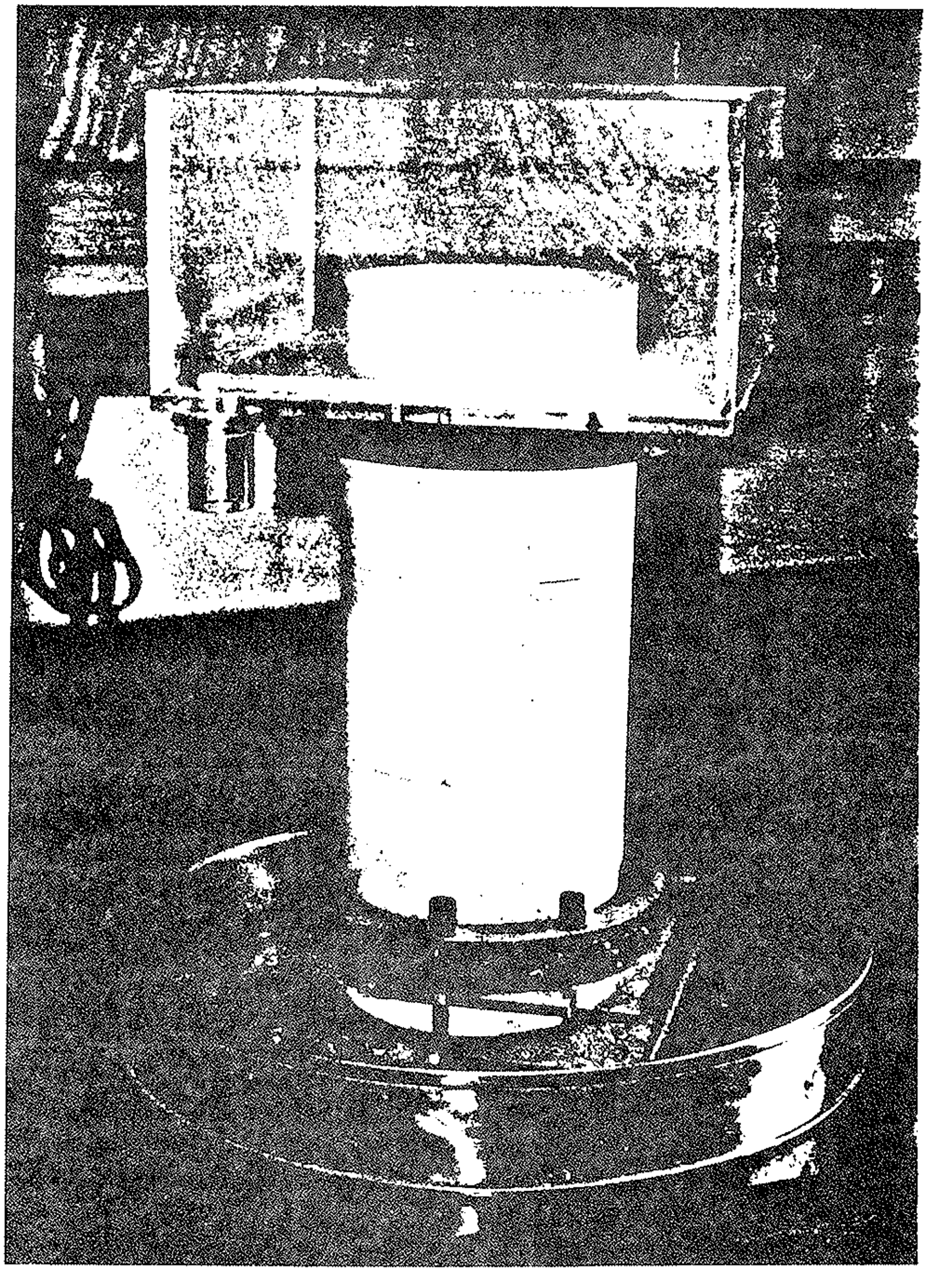


Figure VII-3A

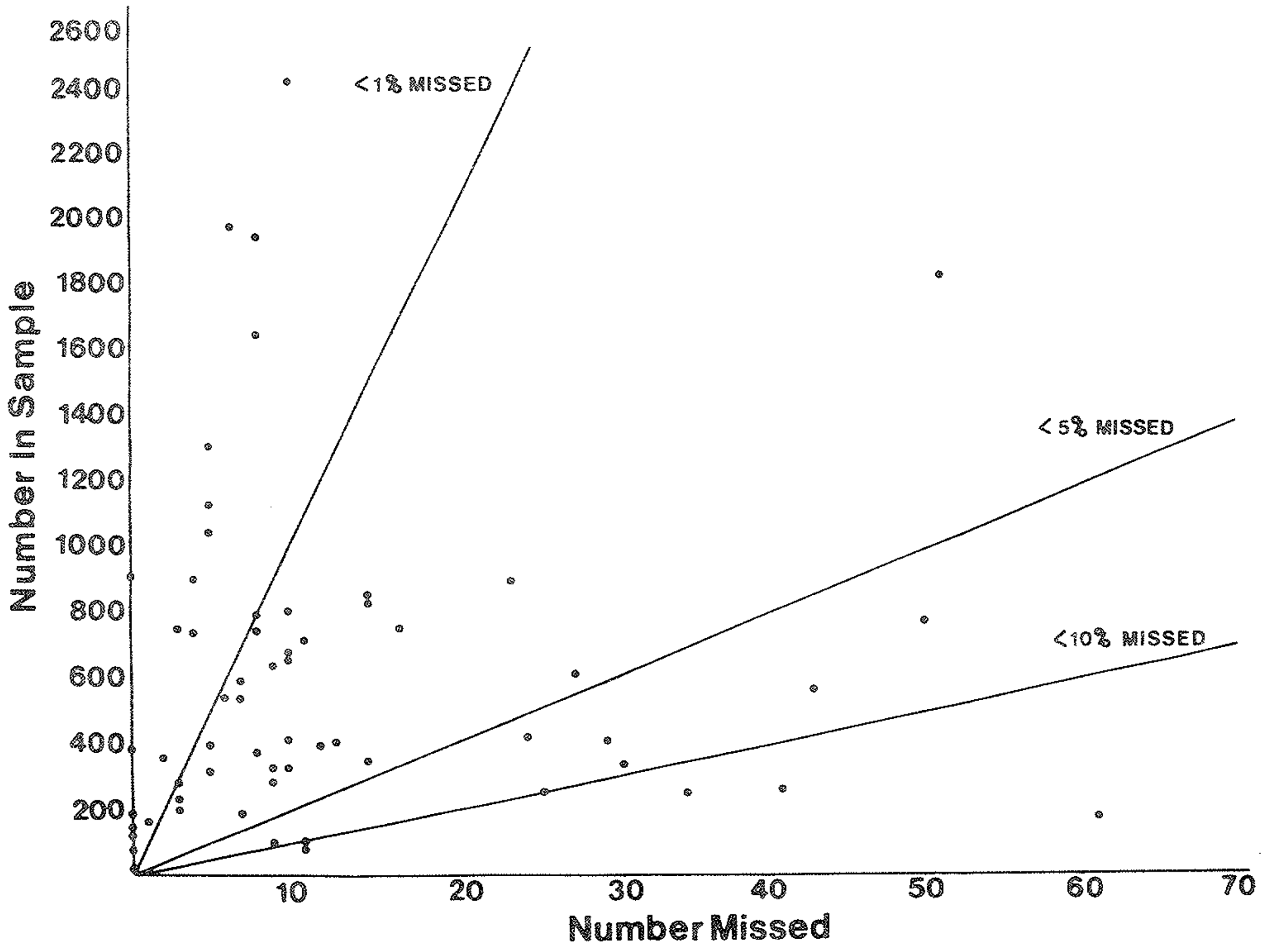


Figure VII-3B

VII-4. SEQUENTIAL SAMPLING

Sequential sampling is a method of analysis that has not been previously applied to freshwater benthic monitoring programs, but which has been used for several years for quality control in industry, the military, and a variety of scientific fields. With this method of statistical inference, the number of required observations is not determined in advance, but rather samples are collected and analyzed sequentially until a decision can be made that meets specified pre-determined levels of precision and risk. Sequential sampling is particularly advantageous in determining whether a given parameter is above or below a critical threshold. In the case of assessing environmental impact using benthic macroinvertebrates (Fig. VII-4A), this parameter could be a community measure (e.g. species diversity) or a population estimate (e.g. density). The most obvious benefit of using sequential sampling is that test procedures can be completed more quickly and at less cost, because fewer observations are needed than with test procedures based on a pre-determined, and often arbitrary, number of observations.

A study site has been selected that is presently uninfluenced by geothermal energy development, although proposed activities may soon impact it; consequently, a monitoring scheme was developed (Fig. VII-4B). To prepare the sequential sampling plan, benthic community diversity (SCI; Cairns et al. 1968) was determined for this undisturbed area. At a nearby site in Big

Sulphur Creek where geothermal energy development has disrupted the benthic community, a lower mean SCI value was observed. Impact is indicated if the cumulative SCI of two samples is <1.19 (e.g. if the sample SCIs were 0.6 and 0.5; filled dot). If the cumulative SCI of the two samples is 1.19<SCI<1.94 (half-filled dot), additional samples must be sorted and their SCIs calculated because a decision line was not crossed. If the no-impact line is crossed (e.g. four SCIs totaling 3.55; unfilled dot), sorting again ceases.

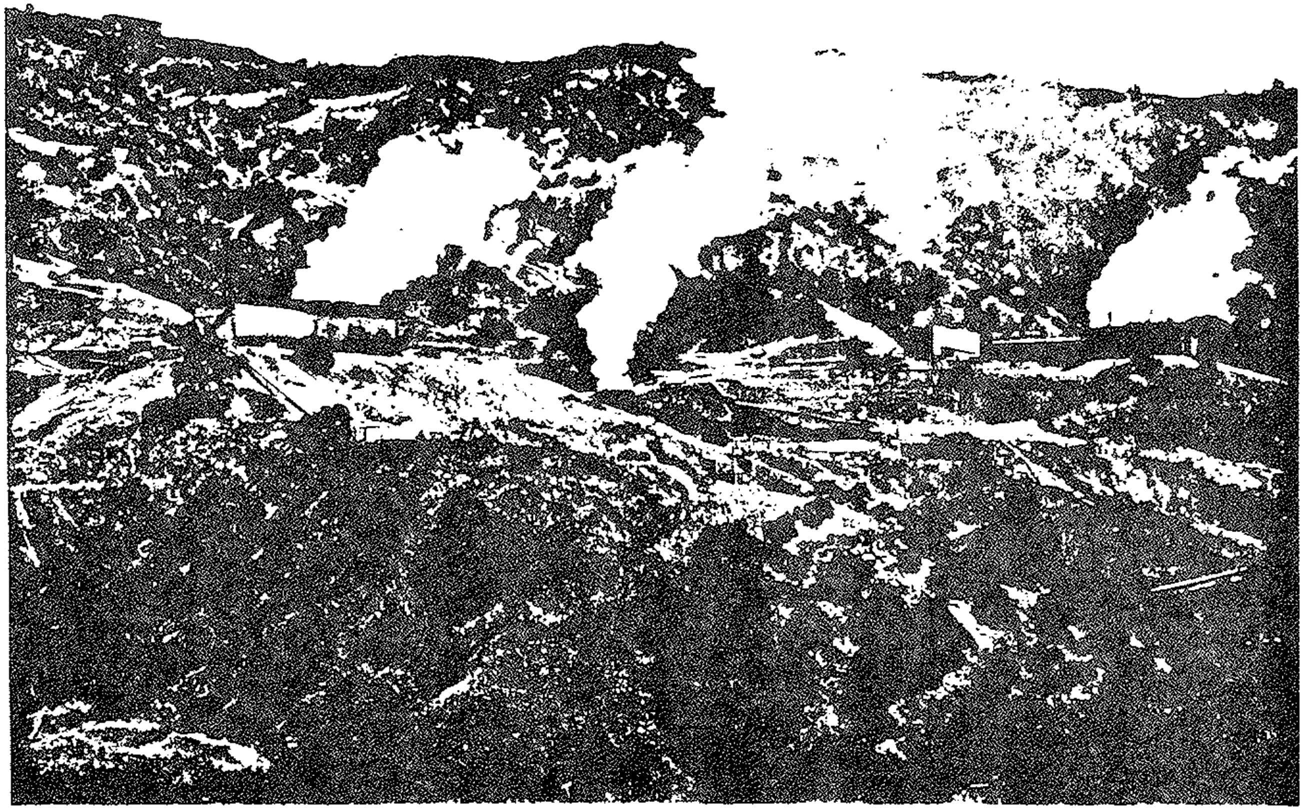


Figure VII-4A

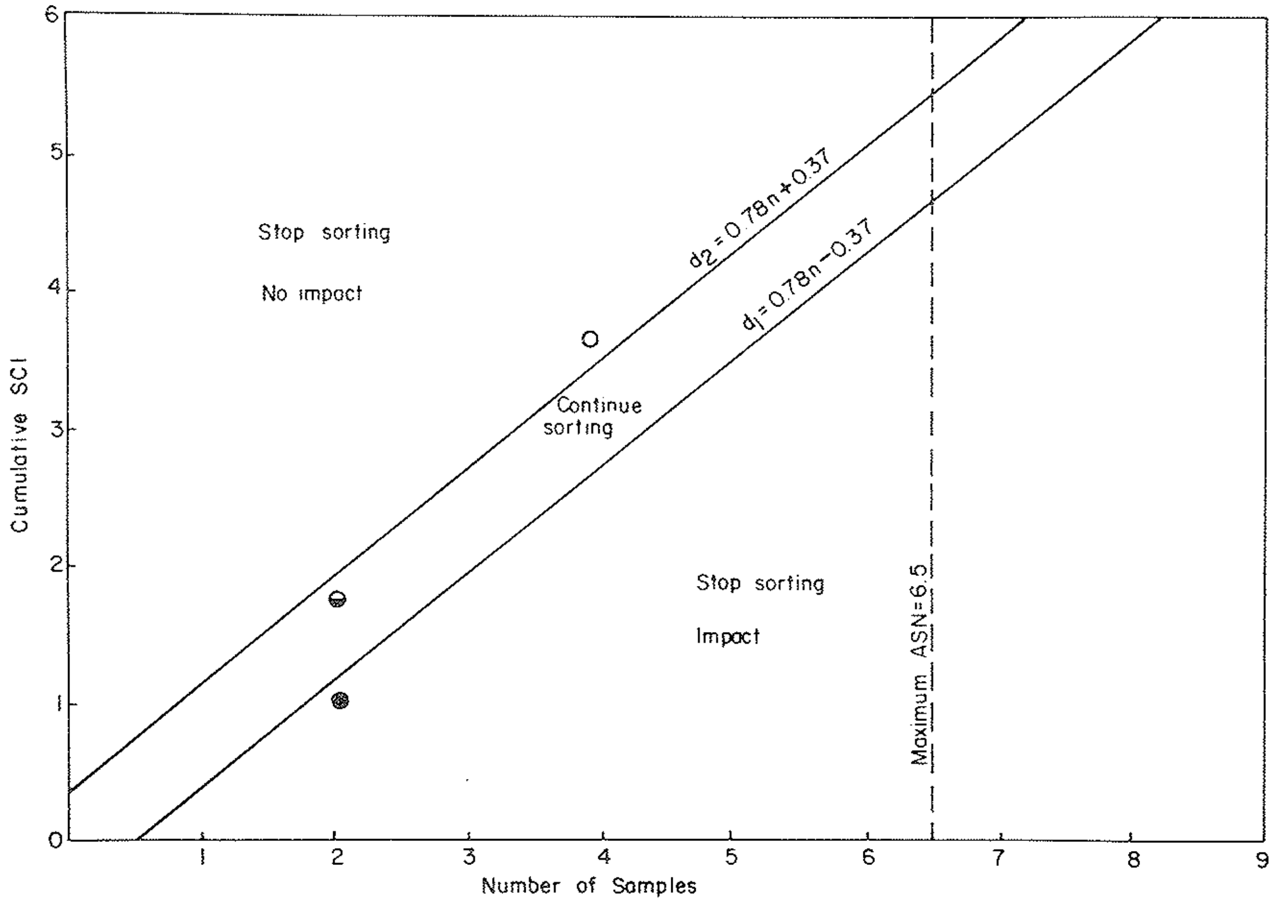


Figure VII-4B

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IX. ASSESSING DROUGHT EFFECTS ON GEOTHERMALLY INFLUENCED STREAMS

INTRODUCTION

California experienced a severe state-wide drought during the years 1975-1977. In the second year of the drought (water year 1976-1977), northern and central California received less than one-third of its normal precipitation (California Department of Water Resources 1977). This resulted in record-low stream flows and serious depletions of reservoirs and groundwater reserves.

The drought ended in the water year 1977-1978, when above-normal precipitation resulted in high stream discharges. Subsequent water years were characterized by more normal precipitation amounts. However, during the water year 1981-1982 precipitation amounts were again well above normal (Table IX-1).

Big Sulphur Creek, as well as other streams in the Known Geothermal Resources Area (K.G.R.A.; Fig.I-1), are typical central California Coast Range streams, characterized by substantial annual fluctuations in discharge. Rainfall is largely restricted to the six-month period from November to April. This results in frequent periods of bankfull or greater stream discharges, which in high-gradient streams such as Big Sulphur Creek produces flow conditions sufficient to displace large boulders and rearrange substrate (i.e. "washout conditions").

From May to October little precipitation falls, and streams characteristically have gradually declining discharges. Thus, during years of well below-normal rainfall, periods of high discharge during the rainy season are much less frequent and severe, and during the following summer stream flows are substantially reduced. This frequently results in increased concentrations of dissolved substances, lower levels of dissolved oxygen due to reduced stream flow and higher temperatures, and reduced habitat area for many forms of aquatic life.

In contrast, during years of above-normal precipitation, periods of high discharge and consequent physical disturbance of the aquatic habitat are more frequent and severe, but during the summer higher flow levels often ameliorate the extreme conditions that are possible during this period.

Literature on the ecological effects of drought and washout is sparse, especially that describing their effects on benthic macroinvertebrates (Hynes 1970). Drought investigations have concentrated on stream intermittency, which is a frequent consequence of drought. Macroinvertebrate communities in intermittent streams typically decline in diversity (e.g. Larimore et al. 1959, Moth Iverson et al. 1978), and are dominated by species that have inactive stages such as diapausing nymphs of certain aquatic insects (e.g. Hynes 1958). The resumption of flow is usually accompanied by rapid recovery of the biota. Partial reduction of streamflow due to drought usually eliminates only a few taxa (Moth Iverson et al. 1978), although the relative abundances of populations may change (Extence 1981).

Washout conditions may seriously affect benthic macroinvertebrate populations, especially rheophilic forms and larger size classes of other groups (Thorup 1970; Barton and Wallace 1979). Several spates in quick succession may defaunate large stream sections (e.g. Fisher et al. 1982).

The primary objective of this study was to evaluate the effect of the 1975-1977 drought on streams in the K.G.R.A. by examining differences in the macrobenthic community structure in Big Sulphur Creek during the period 1977-1982. A second objective was to determine the rate of recovery of certain benthic populations from the drought, once more normal conditions returned.

STUDY AREA

The study was conducted in Big Sulphur Creek (BSC), a third-order stream located in northeastern Sonoma County, California, that flows northwesterly through the K.G.R.A. The drainage basin of BSC is a steep-sided valley in an area characterized by an unstable and highly erodable terrain. Our study site was established at The Geysers 11 km downstream of the headwaters, and within an area of extensive, long-term geothermal energy development. BSC also receives natural geothermal inputs from adjacent hot springs and fumaroles. Stream habitat included mostly small pools and riffles, with substrate varying from sand to large boulders and bedrock outcroppings. Water depth rarely exceeded 0.5 m from spring to autumn, although during winter spates depths as much as 3 m were observed.

EXPERIMENTAL DESIGN AND SAMPLING METHODS

Benthic samples were collected two times each year, during late May and late August/early September from 1977-1982. These two periods were selected to correspond to the prevailing precipitation pattern at The Geysers. By mid to late May, rainfall has generally subsided and spate activity has ended. Macroinvertebrate community structure during this period should reflect losses due to washout conditions associated with winter spates. This date represents a starting point for community development during the summer. The late-August sampling period occurs prior to the onset of rains and catastrophic spates, and reflects the end product of community development over the summer growth period.

Four Surber (0.093 m^2) samples (1.0 mm mesh net) were collected on each sampling date, of which two were located in riffle areas (current velocity > 0.2 m/sec) and two in pool areas (current velocity < 0.2 m/sec). Substrate was excavated to a depth of approximately 5 cm.

Samples were preserved with 10% formalin in the field. In the laboratory, organisms were separated from substrate by washing and decanting through a 135 µm-mesh sieve. Large samples were subsampled, generally by one-quarter. Aquatic insects were identified to the lowest taxonomic level possible and enumerated.

Macroinvertebrate community structure was analyzed by determining species richness (i.e. number of species) and by calculating the inverse of Simpson's index of concentration, a measure of species diversity:

$$C = \frac{\sum n_i (n_i - 1)}{N (N - 1)}; \quad D = \frac{1}{C}$$

where N is the total number of individuals in a sample, and

$\underline{n}_{\underline{i}}$ is the number of individuals of species $\underline{i}$.

Precipitation data at The Geysers resort (adjacent to the study site) was obtained from the National Oceanic and Atmospheric Administration, Hourly Precipitation Data.

RESULTS AND DISCUSSION

Precipitation. Precipitation data collected at The Geysers resort indicates a 25-yr $\bar{x}$ of 147 cm/year (1951-1975). Precipitation data from 1976-1982 indicates that rainfall was <33% of normal during the 1976-1977 wet season (i.e. "drought" year). In contrast, precipitation was >140% of normal during 1977-1978 and 1981-1982 (i.e. "washout" years). The total of 157 cm for winter 1979-1980 was near normal, and the remaining years, 1978-1979 and 1980-1981, were somewhat below normal (Table IX-1).

Since rainfall amounts recorded at The Geysers were strongly correlated ($\underline{r}$=0.97) with stream discharge measured during water year 1977-1978 by a United States Geological Survey hydrograph 7.6 km upstream, rainfall was used as an indicator of stream discharge conditions during the entire study period (there was no operational hydrograph near The Geysers in other water years).

Based on rainfall levels, spates were comparatively mild during the winter preceeding the 1977 samples, and summer flows were substantially reduced compared to normal. Likewise, frequent periods of high winter discharges and elevated summer flow regimes characterized the 1978 and 1982 samples. Stream conditions were closer to normal in the years 1979-1981.

Macroinvertebrate Community Structure. A summary of results from the 6-yr sampling program are presented in Table IX-1. A total of 48 samples were taken and analyzed over this period. Mean number of individuals, Simpson's diversity, and density of the five most abundant taxa in May and August samples are listed for each date and habitat type. A total of 117,686 individuals comprising 96 species were collected during this study.

Considerable differences were observed between May and August densities for all years except the "drought" year (1977). In August of most years, macroinvertebrate density greatly increased from May levels. However, in 1977, August densities increased only slightly from May levels and, in general, riffle densities were much lower than in years with greater summer flows. Under low-flow conditions (e.g. 1977), stresses caused by expected higher concentrations of dissolved substances, lower dissolved oxygen levels, and habitat loss may have adversely affected organisms that typically inhabit riffles during this time. No clear-cut relationship exists between macroinvertebrate densities in May and previous winter rainfall amounts, since low densities are observed during both wet (1978, 1982) and normal (1980) years.

Species richness and Simpson's index are commonly used for analysis of community structure; in addition, the relative abundances of common taxa are of interest since Simpson's index is strongly influenced by dominant taxa. For May samples, both species diversity measurements were low in years following heavy winter rains (e.g. 1978, 1982). Other studies of washout (e.g. Siegfried and Knight 1977) have also shown that such disturbance adversely affects macroinvertebrate communities. However, low values for these indices were also recorded in May 1977, following a very dry winter (i.e. low disturbance). This apparent paradox might be explained by examining the data for August 1977, which followed two summers of extremely low flow (i.e. 1976 and 1977). Species richnesses in both riffles and pools, as well as riffle densities, were considerably lower than for August of the other years, and were probably similar to those of August 1976. Populations in August reflect how the community has developed over the summer and, for many insect species, will constitute a considerable portion of the following May populations, especially if winter spates are not too severe. Thus, it is likely that the low May 1977 diversity reflects the extremely adverse conditions of the previous summer.

A second objective of this study was to determine the rate of recovery of the macrobenthic community from the 1975-1977 drought. "Normal" levels of diversity and macroinvertebrate density were observed the first year that conditions became more favorable (e.g. May 1978 vs. May 1979; August 1977 vs. August 1978). As noted previously, rapid recovery of macrobenthos from catastrophic conditions has been observed in other lotic studies. Apparently, this pattern holds true for Big Sulphur Creek as well.

SUMMARY

We conclude that the disturbance caused by frequent high stream discharges during washout years has an adverse impact, due to physical removal, on macrobenthic diversity and density, as reflected in samples taken at the end of the rainy season but prior to the spring insect emergence peak. Likewise, low summer flows during very dry years have a similarly adverse effect, most likely due to restricted habitat and increased concentrations of dissolved substances. The release of any materials associated with geothermal development would undoubtedly further degrade water quality particularly during periods of minimal discharge (i.e. drought). Although macrobenthic communities of streams in the K.G.R.A., as represented by Big Sulphur Creek, apparently have the capacity to recover from temporary catastrophic events, it is essential that operational practices associated with the development of geothermal energy resources consider the potential impact of geothermal fluids that are allowed to enter natural watercourses.

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Table IX-1. Selected Benthos Parameters, Big Sulphur Creek, 1977-1982.

PARAMETER	1977		1978		1979		1980		1981		1982	
	Riffle	Pool	Riffle	Pool	Riffle	Pool	Riffle	Pool	Riffle	Pool	Riffle	Pool
Previous Winter Rainfall, cm	44.2		216.7		93.4		157.1		95.7		210.4	
BEGINNING OF DRY SEASON (MAY)												
TOTAL NO. TAXA	24	23	17	19	35	37	36	30	26	26	23	20
Mean No. of Individuals	1,077	1,462	175	1,098	1,540	1,243	879	304	894	2,464	267	1,126
Mean Species Diversity	2.26	3.15	1.85	3.01	4.81	4.75	6.40	9.61	9.76	4.27	3.86	2.38
Mean No. Chironomidae OTU #2	697	106	0	0	289	363	267	38	106	194	2	21
Mean No. Chironomidae OTU #8	25	6	5	326	7	17	19	52	76	1,106	20	126
Mean No. Chironomidae OTU #7	8	0	126	556	34	6	24	19	8	57	121	690
Mean No. Baetis	10	9	9	112	593	33	159	16	158	44	40	4
Mean No. Gumaga	1	873	0	0	71	3	0	5	0	52	0	0
END OF DRY SEASON (AUGUST)												
TOTAL NO. TAXA	19	6	28	19	36	24	30	20	25	17	42	19
Mean No. of Individuals	1,531	1,904	6,406	1,842	7,392	1,322	8,869	1,680	10,330	1,063	3,809	223
Mean Species Diversity	3.39	1.14	3.32	1.69	3.00	2.70	3.44	3.20	2.49	2.29	5.26	2.47
Mean No. Chironomidae OTU #2	171	0	2,818	6	3,250	2	3,524	22	6,472	2	1,222	4
Mean No. Helicopsyche	723	80	1,538	843	2,252	722	2,106	586	1,898	28	460	6
Mean No. Gumaga	168	1,792	28	907	62	260	196	556	6	716	1	143
Mean No. Hydropsyche	117	0	776	6	179	2	1,754	6	804	4	533	6
Mean No. Chironomidae OTU #4	215	0	396	53	584	152	274	16	184	24	84	1

X. COMPARISON OF SESTON DYNAMICS IN TWO GEOTHERMAL BASINS

INTRODUCTION

The suspended particulate material (i.e. seston) of running waters is an important energetic resource of those systems (Sedell et al. 1978, Naiman and Sedell 1979, Gurtz et al. 1980). Suspended particulates in streams include both inorganic and organic fractions; the organic component includes detritus, bacteria, and living, dead, or senescent algae (Liaw and MacCrimmon 1977).

Since most streams do not have a true phytoplankton community (Hynes 1970), the source of suspended algae is cells that are sloughed or dislodged from benthic algae (i.e. periphyton). In contrast, bacteria are contributed by both decomposition processes within the stream and inputs of organic material from terrestrial habitats.

The purpose of this study was to determine the abundances of suspended algae and bacteria in three northern California streams, which represented two drainage basins that differed significantly in their geothermal and geochemical characteristics. This research also provided basic information on the seasonal dynamics of suspended microorganisms in small streams that are unaffected, or influenced to varying degrees, by natural geothermal activity and geothermal energy development.

STUDY AREAS

Two drainage basins encompassing three second-order streams within The Geysers K.G.R.A., California (Fig. I-1A), were selected for analyses of suspended microbial communities. The first basin, the Big Sulphur Creek drainage, Sonoma Co., contains Big Sulphur Creek, where extensive geothermal development has occurred, and an adjacent stream, Little Sulphur Creek, where little geothermal development has occurred. The second basin is the Big Canyon Creek, Lake Co., drainage, where a potentially rich geothermal resource exists, but which has thus far been minimally developed (i.e. experimental wells only).

These two basins also have drastically different water chemistries: Big Canyon Creek has a liquid-dominated geothermal reservoir with alkaline conditions and high concentrations of sodium, magnesium, chlorides, and bicarbonates; Big Sulphur Creek has a steam-dominated reservoir with acidic conditions and high concentrations of ammonia and sulfates (McColl et al. 1977). The specific sites chosen for analysis and their characteristics were:

1) Big Sulphur Creek upstream (BSC-U) of a natural geothermal tributary, Little Geysers Creek (LGC):
    A) extensive geothermal development in drainage
    B) acidic, steam-dominated geothermal resource
    C) not influenced by a geothermal fluid input
2) Big Sulphur Creek downstream (BSC-D) of LGC:
    A) extensive geothermal development in drainage
    B) acidic, steam-dominated geothermal resource
    C) influenced by a direct geothermal fluid input
3) Little Sulphur Creek (LSC):

  - A) minimal geothermal development in drainage
  - B) acidic, steam-dominated geothermal resource

4) Big Canyon Creek (BCC):
  - A) minimal geothermal development in drainage
  - B) alkaline, hot water-dominated geothermal resource

METHODS

Samples were collected monthly from each stream site for two years, July 1979 - June 1981. Three subsurface water samples were taken for analyses of: (1) numbers of bacteria; (2) chlorophyll a (an indicator of algal biomass); and (3) phaeophytin (degraded algal chlorophyll).

Bacteria were filtered onto 0.2 μm Nucleopore membranes, stained with acridine orange, and enumerated using epifluorescence microscopy and a direct counting procedure (Barton and Lock 1979). Algae were filtered through glass fiber filters (Whatmen GF/C), extracted in 90% acetone, and chlorophyll a and phaeophytin were measured using spectrophotometry (Moss 1967 a,b).

RESULTS AND DISCUSSION

Big Sulphur Creek: BSC-U cf. BSC-D

Bacterial densities in both BSC-U and BSC-D ranged from 10^5 - 10^6 cells/ml (Fig. X-1). BSC-D generally had higher densities of suspended bacteria, although differences in winter abundances were often small, and in some cases (e.g. November - December 1980), BSC-U densities exceeded those of BSC-D.

Suspended algal pigments, i.e. chloropyll a and phaeophytin (Fig. X-2), displayed more seasonality in abundance than bacteria. Pigment concentrations were generally low (<0.5 µg/l) in BSC-U, but still displayed a gradual increase during the summer and a peak in July, followed by a decline through the winter. Abundances of suspended algae were consistently higher at BSC-D, sometimes reaching 2 µg/l. In particular, algal levels at BSC-D rose dramatically in the spring, but then declined during the winter. There is some evidence for two annual peaks, one in late spring/early summer and another in mid-autumn, much as occurs in lake phytoplankton cycles (Wetzel 1975).

The natural geothermal input of LGC to BSC substantially raises both water temperature and concentrations of certain chemicals at BSC-D (Lamberti and Resh, in review). These influences are greatest during late spring to autumn, when discharge volumes of BSC are also low. Levels of both suspended bacteria and algae at BSC-D indicate that high amounts of those organisms are contributed as well. Seasonal cycles of microbial growth in LGC, together with discharge volumes and other physical factors, probably combine to influence seston dynamics at BSC-D. Clearly, LGC contributes substantial amounts of suspended microorganisms to BSC, in particular during non-winter months. Upstream of that input, BSC-U has the relatively low levels of suspended algae and bacteria that would be expected in a small, forested stream.

Big Canyon Creek (BCC)

Suspended bacteria in BCC ranged from about 1-6 10^5/ml

(Table X-1); bacteria showed little seasonality in abundance, except for an autumn increase in 1979. Winter levels did not markedly decline from summer levels. Winter precipitation and runoff from terrestrial habitats, with associated inputs of bacteria, may account for the maintenance of bacterial levels during that period.

Chlorophyll a and phaeophytin peaked at high levels (to 2 µg/l) during the spring in both 1980 and 1981, when pigment was up to 20-40X higher than winter levels. These spring peaks were probably due to increased benthic primary production, which reflected the higher nutrient inputs from terrestrial sources and increased light during this period. In general, suspended algal biomass was higher during late spring and autumn than during the winter.

Little Sulphur Creek (LSC)

Bacterial density in LSC generally ranged from about 10^5 - 10^6 cells/ml (Table X-1), although >10^6 cells/ml were found during the late summer to autumn (August - November). This autumn peak was up to 10X the levels of other seasons and coincided with extensive inputs of deciduous leaf material to the stream, especially white alder (*Alnus rhombifolia*). Bacterial decomposition processes that operate on this material probably accounted for the high autumn levels of suspended bacteria.

Seasonality in chlorophyll a and phaeophytin were much less pronounced than for bacterial abundance. Algal pigments generally remained at low levels in LSC (<0.5 μg/l), except for a small increase during the late summer in 1980.

Inter-Basin Comparison

Bacterial levels were similar in both basins (i.e. all four study sites) during the winter and spring, during which bacteria were also generally least abundant. Although terrestrial inputs of bacteria probably increased during the winter due to runoff, dilution factors associated with higher winter discharges, coupled with decreased in-stream growth, probably reduced bacterial levels.

Seasonal peaks in bacterial abundance were associated with: (1) inputs of terrestrial leaf material (e.g. into LSC) followed by bacterial decompositon, which increased autumn levels of bacteria; this source can be reduced by geothermal development, which may remove portions of the streamside vegetation; (2) inputs of geothermal fluids (e.g. into BSC-D) that typically carry substantial amounts of suspended bacteria that are sloughed from colonies growing in the favorable thermal regime of the hot spring; this bacterial source was also sustained to some degree during the winter.

Abundances of suspended algae were generally low during winter months, but showed spring and/or autumn peaks at all four study sites. The amplitude of those peaks was highest during the spring in BCC and during both spring and autumn in BSC-D. Algal levels remained relatively low in both LSC and BSC-U.

Seasonal peaks in the abundance of suspended algae were associated with: (1) seasonal cycles in nutrient and light levels; this factor can be influenced by the extent of geothermal development, which can result in removal of streamside vegetation (increased light) and erosion (increased nutrient inputs); (2) inputs of geothermal fluids (e.g. into BSC-D), which contribute high amounts of suspended algae that are sloughed from benthic mats growing in the favorable thermal habitat.

Thus, both the geothermal characteristics of the basin, (especially surface expressions of the resource) and the extent of geothermal development (removal of vegetation; erosion) act jointly to influence the dynamics of suspended bacteria and algae.

Influence of Seston on Benthic Macroinvertebrates

Suspended organic material is potentially available as food to macroinvertebrate consumers, especially filter-feeding species, and thus serves as an important trophic link between invertebrate communities and primary producers/decomposers in running waters (see review by Wallace and Merritt 1980). Bacteria and algae are more easily assimilable than the detrital components of seston (Lamberti and Moore, in press), and thus assume additional importance in the feeding and growth of invertebrate consumers.

The analysis of constituents of geothermal waters has been advocated for use in evaluating environmental degradation by effluents from geothermal energy development (Axtmann 1975). Similarly, the analysis of biotic components of these same systems, such as seston, has great potential for evaluating changes in environmental quality.

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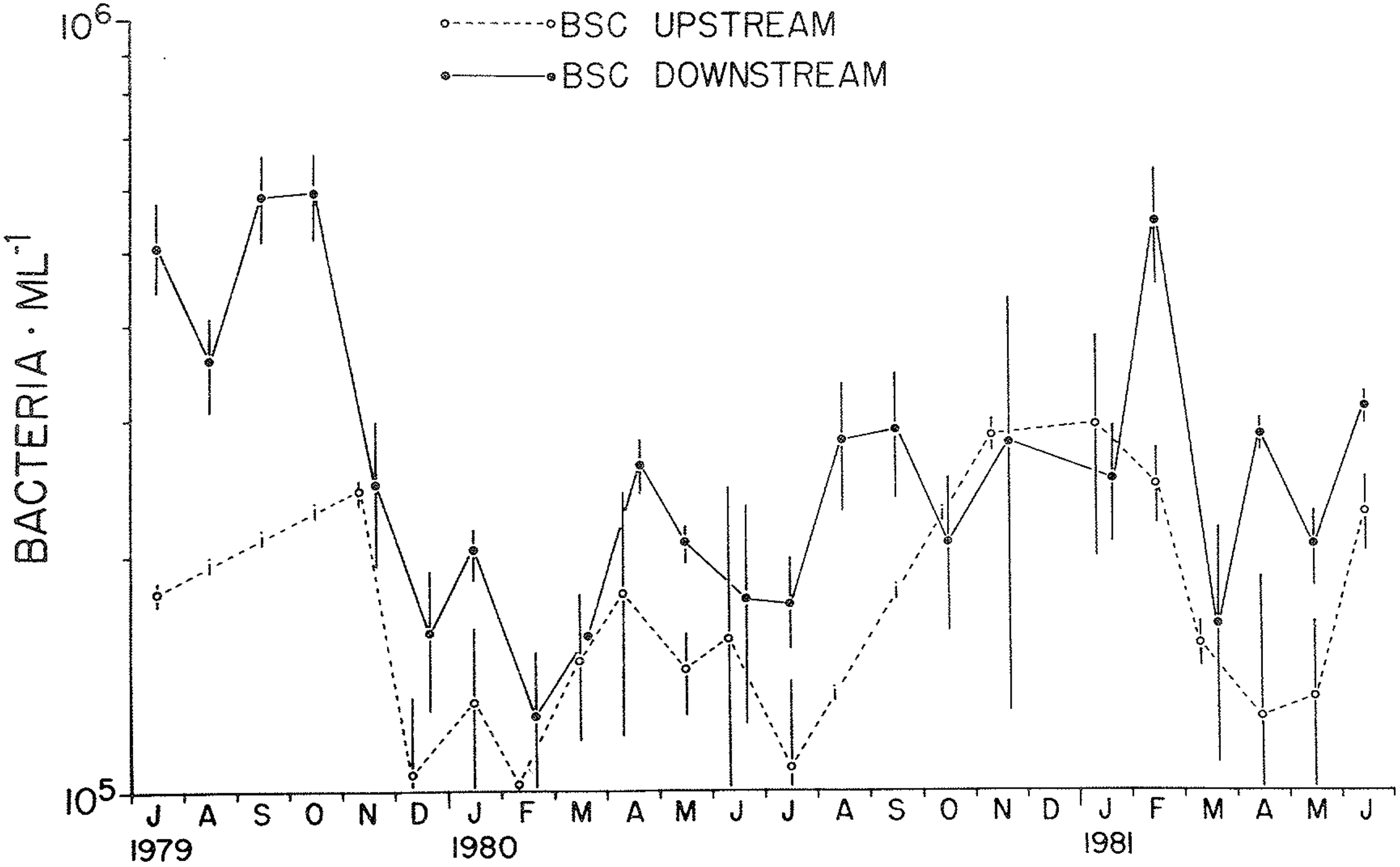
TABLE X-1. Abundances of suspended bacteria (no·10^5/ml), chlorophhyll a (µg·10/l), and phaeophytin (µg·10/l) in Little Sulphur Creek (LSC) and Big Canyon Creek (BCC) from 1979-1981; NA = not available; BD = below detection.

Year/	Bacteria		Chlorophyll a		Phaeophytin	
Month	LSC	BCC	LSC	BCC	LSC	BCC
1979						
J	8.5	2.1	1.8	2.4	1.9	3.3
A	8.2	1.7	1.6	2.1	1.8	2.8
S	10.7	3.4	1.3	3.4	2.1	3.2
O	13.9	5.9	0.6	2.5	1.1	3.3
N	2.5	2.4	BD	1.1	BD	1.3
D	1.7	1.8	1.0	1.7	1.4	2.4
1980						
J	1.7	1.5	0.5	1.1	1.4	2.7
F	2.5	1.8	BD	BD	BD	BD
M	1.6	NA	0.4	1.1	0.9	2.4
A	1.9	1.6	0.4	4.1	0.6	4.1
M	1.5	1.7	0.3	22.0	1.3	6.4
J	1.0	0.9	0.8	4.4	2.0	3.7
J	7.7	1.5	1.6	1.1	1.3	1.9
A	13.1	1.1	2.9	2.8	4.6	2.0
S	8.4	1.3	0.3	4.6	1.9	4.2
O	7.2	1.5	1.8	4.9	0.4	4.0
N	5.8	1.9	1.0	1.3	1.3	2.1
D	2.9	1.6	BD	0.5	BD	1.0
1981						
J	0.9	2.2	0.4	2.6	0.6	4.5
F	1.8	1.3	1.3	2.4	0.3	1.8
M	1.7	1.4	0.5	2.8	0.2	2.6
A	1.0	1.1	BD	1.7	BD	2.6
M	1.8	2.8	0.9	5.8	0.9	6.4
J	9.7	3.4	2.5	2.7	2.8	3.6



BSC UPSTREAM
BSC DOWNSTREAM
10^6
10^5
BACTERIA · ML^-1
J
A
S
O
N
D
J
F
M
A
M
J
J
A
S
O
N
D
J
F
M
A
M
J
1979
1980
1981

Figure X-1

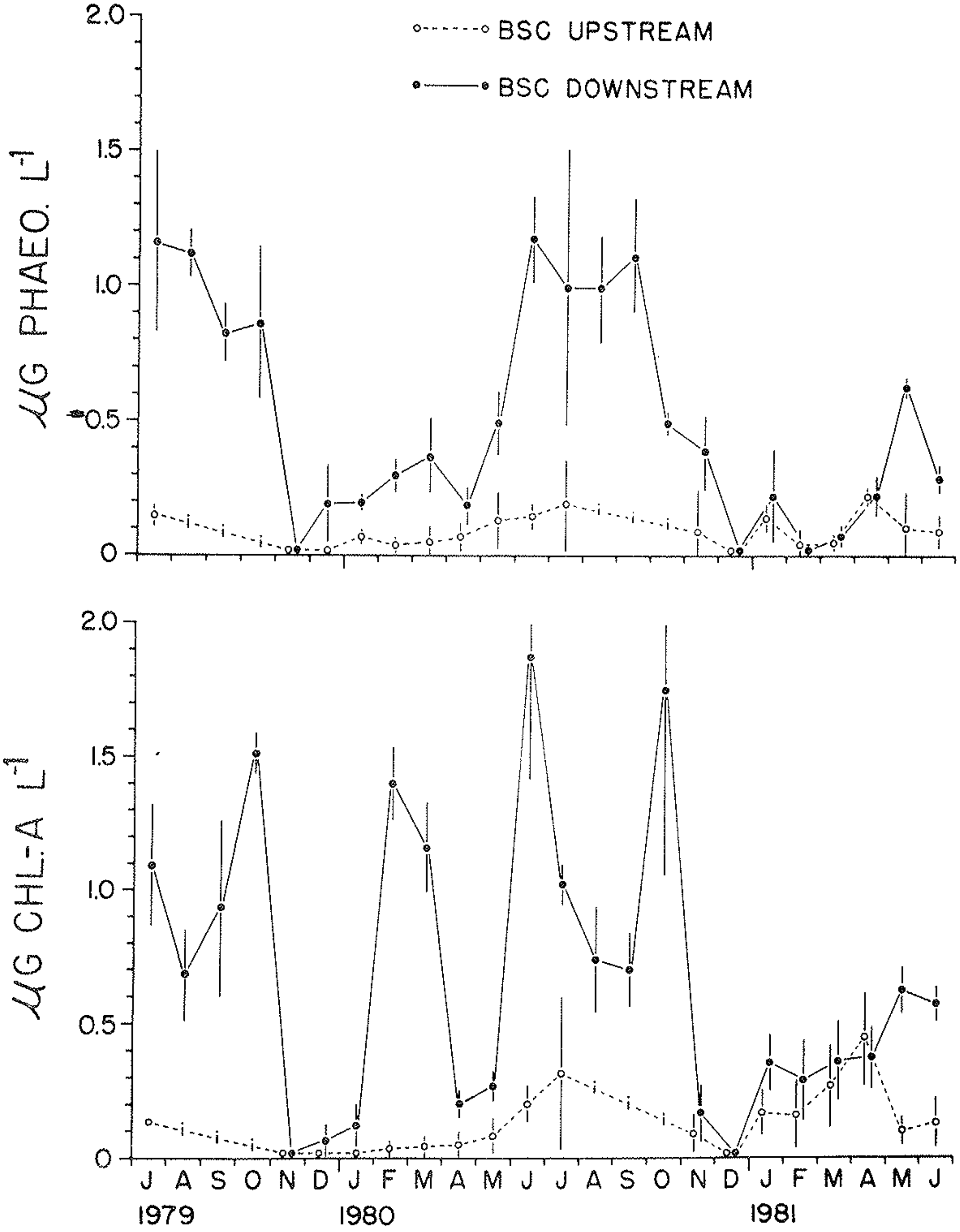

2.0
1.5
1.0
0.5
0
BSC UPSTREAM
BSC DOWNSTREAM
µG PHAEO. L⁻¹
µG CHL-A L⁻¹
J
A
S
O
N
D
J
F
M
A
M
J
J
A
S
O
N
D
J
F
M
A
M
J
1979
1980
1981

Figure X-2

ACKNOWLEDGEMENT

The research leading to this report was supported in part by the United States Department of the Interior, under the Matching Grant Program of Public Law 95-467, Project No. B-200-CAL, and by the University of California Water Resources Center, Project UCAL-WRC-W-548. Contents of this publication do not necessarily reflect the views and policies of the Bureau of Reclamation, United States Department of the Interior, nor does mention of trade names or commercial products constitute their endorsement or recommendation for use by the U.S. Government.